



REDD SITE SELECTION AND SPAWNING HABITAT USE BY FALL CHINOOK
SALMON, HANFORD REACH, COLUMBIA RIVER

Final Report 1995 – 1998

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ABSTRACT

This report summarizes results of research activities conducted from 1995 through 1998 on identifying the spawning habitat requirements of fall chinook salmon (*Oncorhynchus tshawytscha*) in the Hanford Reach of the Columbia River. The project investigated whether traditional spawning habitat models could be improved in order to make better predictions of available habitat for fall chinook salmon in the Snake River. Results suggest models could be improved if they used spawning area-specific, rather than river-specific, spawning characteristics; incorporated hyporheic discharge measurements; and gave further consideration to the geomorphic features that are present in the unconstrained segments of large alluvial rivers. Ultimately the recovery of endangered fall chinook salmon will depend on how well we are able to recreate the characteristics once common in alluvial floodplains of large rivers. The results from this research can be used to better define the relationship between these physical habitat characteristics and fall chinook salmon spawning site selection, and provide more efficient use of limited recovery resources.

This report is divided into four chapters which were presented in the author's doctoral dissertation which he completed through the Department of Fisheries and Wildlife at Oregon State University. Each of the chapters has been published in peer reviewed journals or is currently under review. Chapter one is a conceptual spawning habitat model that describes how geomorphic features of river channels create hydraulic processes, including hyporheic flows, that influence where salmon spawn in unconstrained reaches of large mainstem alluvial rivers.

Chapter two describes the comparison of the physical factors associated with fall chinook salmon redd clusters located at two sites within the Reach. Spatial point pattern analysis of redds showed that redd clusters averaged approximately 10 hectares in area and their locations were consistent from year to year. The tendency to spawn in clusters suggests fall chinook salmon's use of spawning habitat is highly selective. Hydraulic characteristics of the redd clusters were significantly different than the

habitat surrounding them. Velocity and lateral slope of the river bottom were the most important habitat variables in predicting redd site selection. While these variables explained a large proportion of the variance in redd site selection (86 to 96%), some unmeasured factors still accounted for a small percentage of actual spawning site selection.

Chapter three describes the results from an investigation into the hyporheic characteristics of the two spawning areas studied in chapter two. This investigation showed that the magnitude and chemical characteristics of hyporheic discharge were different between and within two spawning areas. Apparently, fall chinook salmon used chemical and physical cues from the discharge to locate spawning areas.

Finally, chapter four describes a unique method that was developed to install piezometers into the cobble bed of the Columbia River.

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Chapter 1. Redd Site Selection and Spawning Habitat Use by Fall Chinook Salmon:
the Importance of Geomorphic Features in Large Rivers

David R. Geist and Dennis D. Dauble

ABSTRACT

Knowledge of the three-dimensional connectivity between rivers and ground-water within the hyporheic zone can be used to improve the definition of fall chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat. Information exists on the micro-habitat characteristics that define suitable salmon spawning habitat. However, traditional spawning habitat models that use these characteristics to predict available spawning habitat are restricted because they can not account for the heterogeneous nature of rivers. We present a conceptual spawning habitat model for fall chinook salmon that describes how geomorphic features of river channels create hydraulic processes, including hyporheic flows, that influence where salmon spawn in unconstrained reaches of large mainstem alluvial rivers. Two case studies based on empirical data from fall chinook salmon spawning areas in the Hanford Reach of the Columbia River are presented to illustrate important aspects of our conceptual model. We suggest that traditional habitat models and our conceptual model can be combined to predict the limits of suitable fall chinook salmon spawning habitat, as well as incorporate quantitative measures of river channel morphology, including general descriptors of geomorphic features at different spatial scales. Techniques to measure and quantify hyporheic flow must be used to understand the processes influencing redd site selection and spawning habitat use. This information is needed in order to protect existing salmon spawning habitat in large rivers, as well as to recover habitat already lost.

INTRODUCTION

The protection and restoration of spawning habitat within large mainstem rivers is included in most recovery plans for Pacific salmon (USFWS 1991; NPPC 1994; USFWS 1996a, 1996b). Realistic predictions of available spawning habitat must be used to define salmon recovery goals (ISG 1996). However, we have little knowledge

of spawning site use by salmon beyond our understanding of the physical constraints imposed on site selection, redd construction, and embryo survival. One widely used traditional spawning habitat model, the Physical Habitat Simulation model (PHABSIM; Milhous 1979; Stalnaker 1979) of the Instream Flow Incremental Methodology (IFIM; Bovee 1982) uses estimates of water depth, water velocity, and substrate size (standard spawning habitat characteristics) to predict available spawning habitat. Spawning habitat characteristics are collected along transects that are placed in the study area. The transects divide the study area into a series of rectangular cells (plan view) with each cell a unique combination of depth, substrate, and velocity. The IFIM uses hydraulic simulation models to predict how depth and velocity will change with discharge. A habitat quality index is estimated for each cell when the predicted water depth, velocity, and substrate for that cell are evaluated against the microhabitat criteria used to define spawning habitat. Microhabitat is usually measured from individual redds located within the river of interest. The habitat quality index is multiplied by the surface area of the cell to obtain an index of spawning habitat. If the indices of spawning habitat in each cell are summed over the entire study site, then an estimate of the total available spawning habitat can be obtained for a series of simulated discharges. The pros and cons of using IFIM and PHABSIM to model fish habitat have been debated in the literature (Mathur et al. 1985; Orth and Maughan 1986; Mathur et al. 1986). The IFIM approach has been useful for defining the limits of salmon spawning habitat, but in some situations where PHABSIM has been used, estimates of available spawning habitat were questionably high (Shirvell 1989; Arnsberg et al. 1992) suggesting that either some other variables are involved or that the spatial scale upon which the suitability criteria were developed was too coarse. More realistic estimates of salmon spawning (i.e., relative to known escapement) have been made with PHABSIM when river channel slope and scour potential were added as model parameters (Connor et al. 1994a, 1994b) suggesting that predictions of available spawning habitat for salmon by traditional models such as PHABSIM are improved by including characteristics that consider river channel hydraulics.

In our studies of fall chinook salmon (*Oncorhynchus tshawytscha*) spawning in the Hanford Reach of the Columbia River, we have noted that fall chinook salmon redds are usually aggregated in definite clusters even though it appears suitable spawning areas are widely distributed (Dauble and Watson 1990). These clusters (Figure 1.1) tend to occur in areas with complex channel pattern, rather than where the channel is straight and simple. Measurements of water velocity, substrate size, and water depth made at the micro-habitat scale (scale of an individual redd, i.e., 10^0 m) from redds throughout the entire Hanford Reach were not related to the distribution of these spawning clusters (D.R. Geist, unpublished data). The patchy distribution of fall chinook salmon redds in relation to available depth, substrate, and velocity suggested that fall chinook salmon have relatively specific spawning habitat requirements that were not represented by micro-habitat characteristics used in PHABSIM. We believe that these complex channel patterns create geomorphic bed forms at the sediment/water interface that promote the development of interstitial flow pathways between surface water and groundwater.

Although we believe that salmon respond to physical features of habitat at the micro-habitat scale, the form and structure of the physical features at this scale are constrained by geomorphic features of river channels occurring at larger scales. Thus, we argue that traditional salmon spawning habitat models need to incorporate additional characteristics of channel features that are measured at spatial scales reflective of the geomorphic processes that formed them, and that these additional characteristics represent geomorphic features of river channels that promote the horizontal and vertical flow pathways between surface water and groundwater. It is possible that estimates of available salmon spawning habitat in large mainstem rivers may be improved by incorporating geomorphic features that influence interstitial flow pathways between surface water and groundwater.

The objective of this paper is to present a conceptual spawning habitat model for fall chinook salmon that describes how geomorphic features of river channels affect hydraulic processes, including hyporheic flows, and in turn, how these hydraulic processes influence where salmon spawn in unconstrained reaches of large mainstem

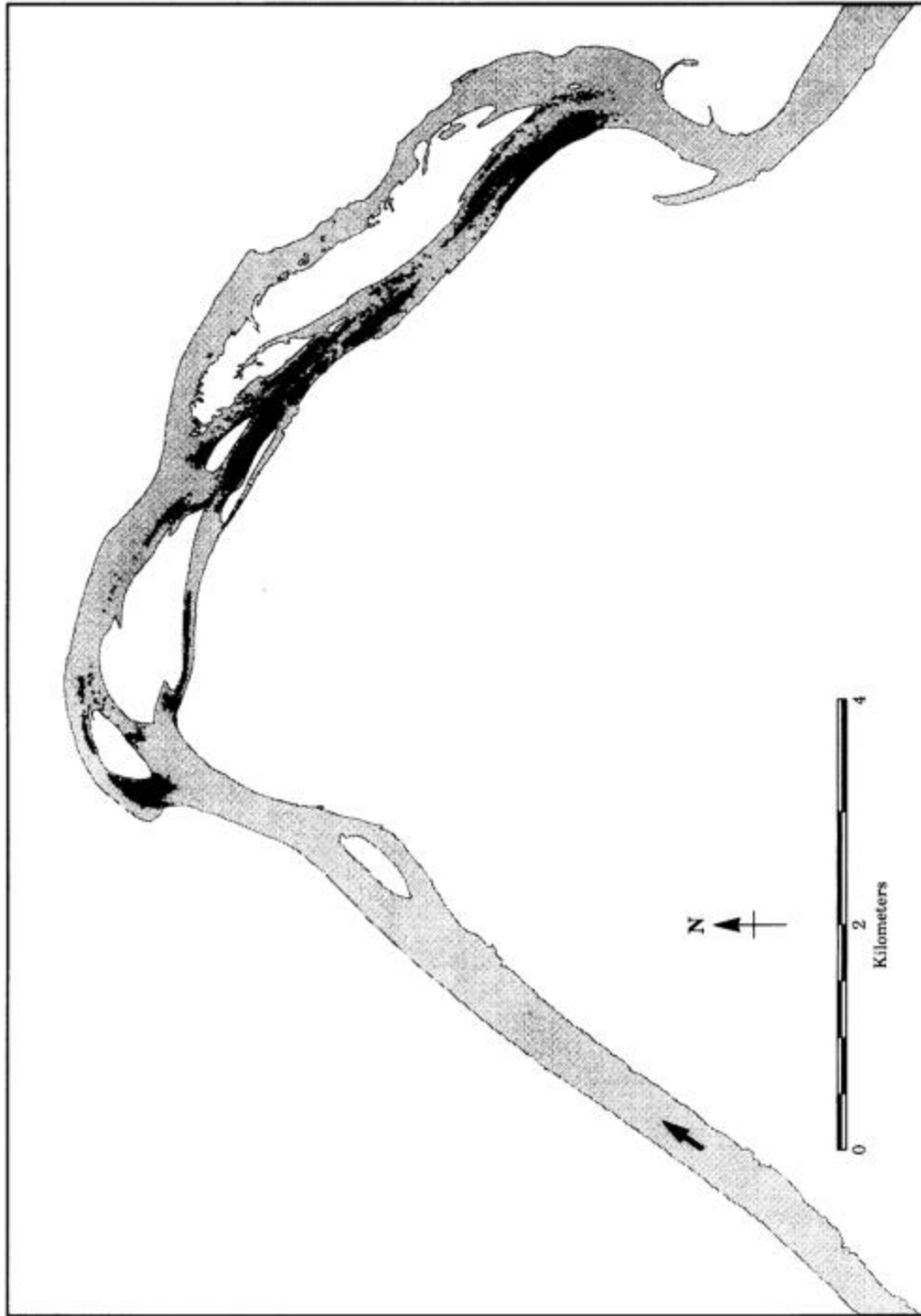


Figure 1.1. A section of the Hanford Reach of the Columbia River showing several typical fall chinook salmon (*Oncorhynchus tshawytscha*) spawning clusters. Each dot represents an individual salmon nest (redd) that was digitized into a Geographic Information System from aerial photographs taken during 1994 and 1995 at peak spawning (mid-November). The arrow indicates flow direction.

alluvial rivers. The distinction between large and small rivers is arbitrary since the geometry and hydraulic aspects of rivers are often similar in small shallow streams and large deep rivers (Stalnaker et al. 1989). Two case studies are presented to illustrate important aspects of our conceptual model. The first case study presents evidence that the hyporheic zone within a fall chinook salmon spawning area was comprised of varying proportions of groundwater and surface water that were interactive with one another. The second case study demonstrates the limitations of using micro-habitat characteristics (in this case substrate) for predicting useable fall chinook salmon spawning habitat. Although much of the empirical data discussed in the case studies were collected in the Hanford Reach, we believe this information is applicable to protection and restoration of endangered fall chinook salmon in the Snake River and that this model provides insight into new ways of quantifying spawning habitat for other species of salmonids in other freshwater systems.

INFLUENCES OF GEOMORPHIC FEATURES ON SALMON SPAWNING HABITAT

River systems are best viewed as hierarchically organized geomorphic features arranged predictably within a watershed (Frissell et al. 1986; Schlosser and Angermeier 1995). At progressively higher levels of organization, large rivers incorporate micro-habitat (10^0 m), pools and riffles (10^1 m), river reaches (10^2 to 10^3 m), segments of watersheds (10^4 to 10^5 m), and entire watersheds ($\geq 10^6$ m). The hierarchy is spatially nested, i.e., a geomorphic feature at one level affects the form and function of the geomorphic features at a lower level (Frissell et al. 1986; Grant et al. 1990; Gregory et al. 1991). For example, geomorphic features at the “section or segment scale” (i.e., regional landforms that reflect different landscape formations) affect channel features at the “reach scale” (i.e., defined by the degree of lateral constraint and usually consisting of integrated geomorphic units). Examples of reach features in large, alluvial rivers include gravel bars and islands that are longer than one channel width in length. The location and morphology of these features in turn affect specific hydraulic features of

the spawning habitat at the “channel unit scale or pool/riffle system” (i.e., distinct hydraulic and geomorphic structures with characteristic bed topography, water surface slope, depth, and velocity patterns) and those at the “sub-unit or micro-habitat” scale (i.e., transitory hydraulic features within a channel unit that have homogenous substrate type, water depth, and velocity).

One important and often overlooked hydraulic process that occurs within unconstrained reaches of large, alluvial rivers is the interaction of groundwater and surface water within the hyporheic zone. The hyporheic zone has been described in various ways [see reviews by White (1993) and Brunke and Gonser (1997)], but is generally considered to be the sub-surface region of streams and rivers that contains a mix of groundwater and surface water (Valett et al. 1993). The characteristics of the hyporheic zone vary widely in space (Brunke and Gonser 1997), and consequently there are many interstitial flow pathways that occur between rivers and the hyporheic zone. For example, localized upwelling and downwelling is largely a function of the river bed topography and the permeability and depth of alluvium, whereas large-scale exchange processes are determined mainly by geomorphic features of river channels (i.e., gravel bar location and morphology, meander pattern, channel roughness, hydraulic conductivity, and hydraulic gradient; Vaux 1962; Vervier et al. 1992; Harvey and Bencala 1993; Brunke and Gonser 1997; Figure 1.2). In general, the change in river bed topography relative to water depth in areas of aggraded sediments (e.g., upstream end of an alluvial floodplain, “crossing” or inflection point of a channel meander, or the upstream end of a riffle or gravel bar) creates a high pressure zone where surface water downwells into the sediments, displacing interstitial water (Brunke and Gonser 1997). The interstitial water then flows through the aquifer, and upwells to the channel where the hydraulic gradient of the subsurface water equals that of the channel bed and a low pressure zone is created (Vaux 1962, 1968; White 1993). Upwelling areas represent hyporheic flow entering the surface water, and includes both groundwater and surface water that has passed through permeable substrate (White 1993).

Geomorphic bed forms of the river “set up” sites for localized upwelling and downwelling, but the relative mix of groundwater and surface water in the hyporheic zone is also a function of the water level of the river and the quantity of regional groundwater discharge to the river. For example, during spring run-off the higher river level forces water into the bed-forms of the river and dilutes the regional groundwater discharge. Consequently, the hyporheic zone may be comprised of mostly river water. The opposite is true during periods of low river flow where regional groundwater in the hyporheic zone is more predominant. In regulated rivers this alteration between high and low river stage (i.e., discharge) occurs much more frequently and, consequently, affects the relative mix of groundwater and surface water in the hyporheic zone more often.

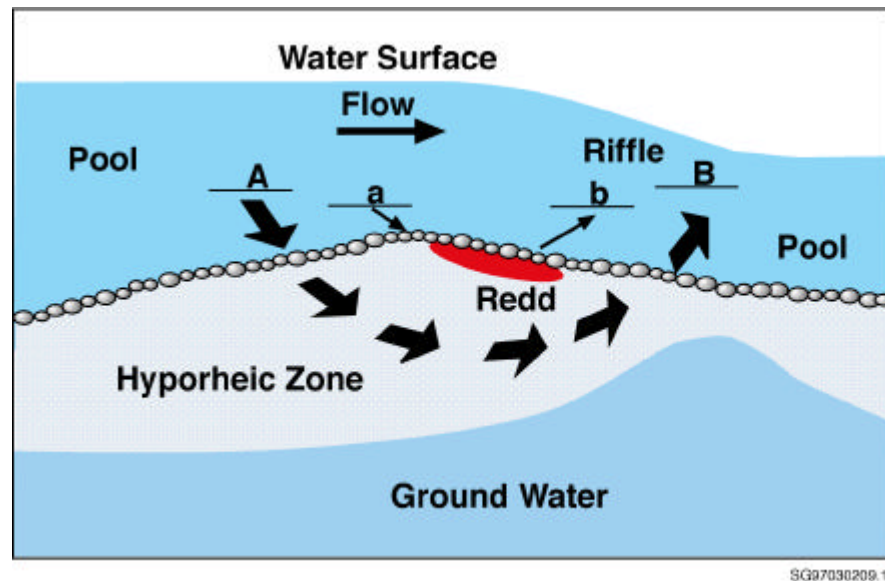


Figure 1.2. Conceptual model of the hyporheic zone using a longitudinal profile of a hypothetical river channel (after White 1993). Flow into and out of the hyporheic zone is a result of higher hydraulic pressure on the pool side versus riffle side and occurs at more than one spatial scale. For example, a and b depict areas of localized downwelling and upwelling, respectively, at the micro-habitat or sub-unit (i.e., redd) scale. A and B depict areas of downwelling and upwelling, respectively, at the channel unit (i.e., pool-riffle) scale (scale is exaggerated).

The hyporheic zone is the primary connection between groundwater and surface water within unconstrained reaches of large, alluvial rivers (Stanford et al. 1996). Unconfined flow is vertically and laterally dynamic with the surface water, and the convergence of the surface and groundwater may be critically important in the formation of river channel morphology (Hynes 1983; Stanford and Ward 1993; Hakenkamp et al. 1993). The alluvial nature of rivers results in river beds and their floodplains being networks of inter-connected surface and groundwater flow pathways lateral to the river channel that occur within the hyporheic zone at both large and small spatial scales (Figure 1.3). Conceptualizing the hyporheic zone as a corridor (Stanford and Ward 1993) that extends laterally within the floodplain and longitudinally along the river profile provides a working model that integrates the geomorphic features of river channels across the hierarchy of spatial scales (Ward 1989).

CONCEPTUAL SPAWNING HABITAT MODEL

We propose that salmon redd distribution within large alluvial rivers may be a function of the interaction of surface water and groundwater via the hyporheic zone. Traditional spawning habitat models cannot represent the heterogeneous features of river channels because they do not include variables that represent the hydraulic characteristics associated with interstitial flow pathways. Thus, our conceptual spawning habitat model includes additional characteristics that we suggest represent geomorphic features of river channels promoting the horizontal and vertical flow pathways within the hyporheic zone (Table 1.1). These features are related across a range of spatial scales. For example, the longitudinal profile of a river reach (reach scale) is reflective of its long-term geological development (segment or section scale; Frissell et al. 1986). Under conditions of uniform discharge, a direct relationship exists between slope and bed material particle sizes (Richards 1982). Thus, longitudinal slope will largely determine substrate available for spawning (channel unit or micro-habitat scales) unless substrate size is influenced by inputs from tributaries or bank erosion. In unconstrained reaches of large gravel- and cobble-bed rivers, the longitudinal slope is reduced and

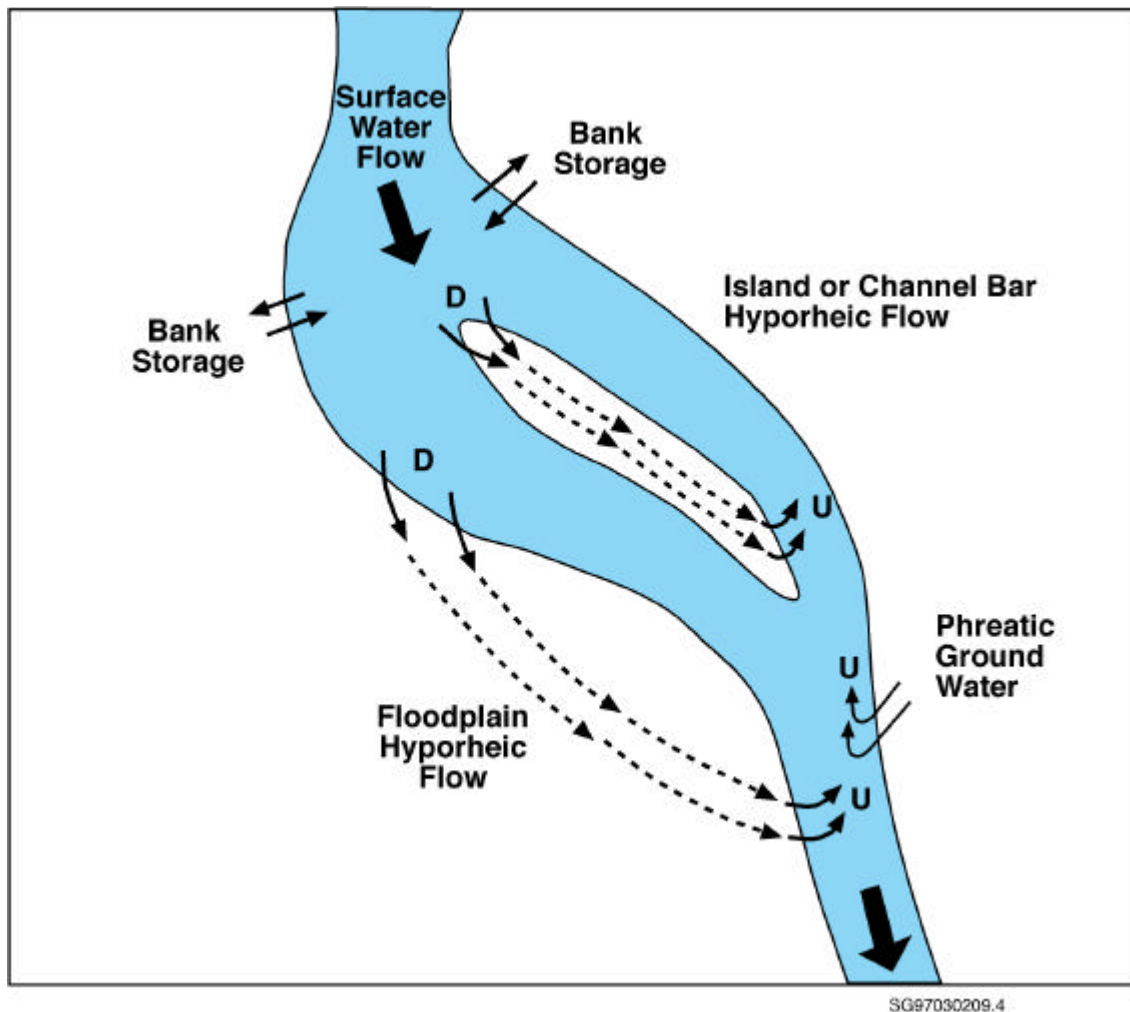


Figure 1.3. Conceptual model of hyporheic flow within an unconstrained alluvial floodplain reach of a large river (plan view). Hyporheic flow within the river bank, islands, and floodplain is a function of channel pattern, morphology, and hydraulic connectivity of the alluvial material and can occur at more than one spatial scale (i.e., island, channel bar, and floodplain). U and D depict areas of upwelling and downwelling.

alluvium is deposited (Stanford et al. 1996). This alluvium is highly porous, allowing river water to penetrate into the bed material, and creating interstitial flow pathways that link surface water and groundwater within the hyporheic zone (Stanford and Ward 1993). These conditions result in heterogeneous salmon spawning habitat (micro-habitat scale).

Channel morphology (channel pattern, channel islands, bedforms, and lateral activity; Kellerhals and Church 1989) is another component of our conceptual spawning habitat model (Table 1.1). Channels that are capable of carrying sediment result in the development of lateral and point bars (Church and Jones 1982). Salmonid spawning usually occurs at the transition between pools to riffles (Bjornn and Reiser 1991; Figure 1.2), which are areas often associated with a lateral bar deposition area (Church and Jones 1982). Downwelling and upwelling of hyporheic flow occurs at the upstream and downstream portions of a channel bar or island (reach or channel unit scale, depending on size) creating interstitial flow pathways through the bed material (Brunke and Gonser 1997). Additionally, the inside edge of a channel bend may have strong flow divergence and non-laminar velocity patterns would be more prevalent in areas of channel bifurcation (Leopold et al. 1964). A quantitative measure of channel pattern can be made by plotting segment azimuth versus channel distance, allowing an investigator to determine thalweg (i.e., deepest part of the channel) configuration (Brice 1973 from Richards 1982). The more complex the channel pattern, the more likely are downwelling and upwelling zones (Brunke and Gonser 1997) which will result in increased habitat heterogeneity (Stanford et al. 1996), and may ultimately affect the specific locations salmon spawn (micro-habitat scale).

Traditional salmon spawning habitat models like PHABSIM are useful in predicting usable habitat because they use “traditional characteristics” that define the limits to where salmon can successfully spawn (Table 1.1). However, the input parameters for PHABSIM are very specific, and incorporating our “additional characteristics” into it may be difficult because of the strict programming code used in PHABSIM. An alternative approach would be to combine PHABSIM with our conceptual model using

Table 1.1. List of typical physical habitat parameters used in previous studies to describe fall chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat (empirically derived) and other additional characteristics that we suggest could be included. Traditional characteristics are usually measured at the micro-habitat scale (10^0 m) in large rivers. Additional characteristics could be measured at various spatial scales.

Traditional characteristics	Additional characteristics
Water depth	Longitudinal and transverse slope
Water velocity	Channel morphology (channel pattern, channel islands, bedforms, and lateral activity)
Substrate size	Hyporheic temperature, dissolved oxygen, pH, and electrical conductivity
	Near-bed velocity gradient
	Vertical hydraulic gradient (upwelling and downwelling)
	Substrate depth, stability, permeability, and porosity
	Hydraulic conductivity and transmissivity
	Presence or absence of natural bedforms (e.g., dunes and/or ripples) and their type, shape, amplitude, frequency, etc.
	Rate of bedform migration
	Presence of groundwater springs

Geographic Information Systems (GIS). A hypothetical example of this approach is illustrated in Figure 1.4. A spawning habitat polygon (SHP) is quite large when “traditional characteristics” are used to define suitable spawning habitat (Figure 1.4). This is because traditional characteristics are not always uniquely associated with the spawning areas. Consequently, most of the redds within the spawning area are included within the SHP, but much of the river reach not used for spawning is also

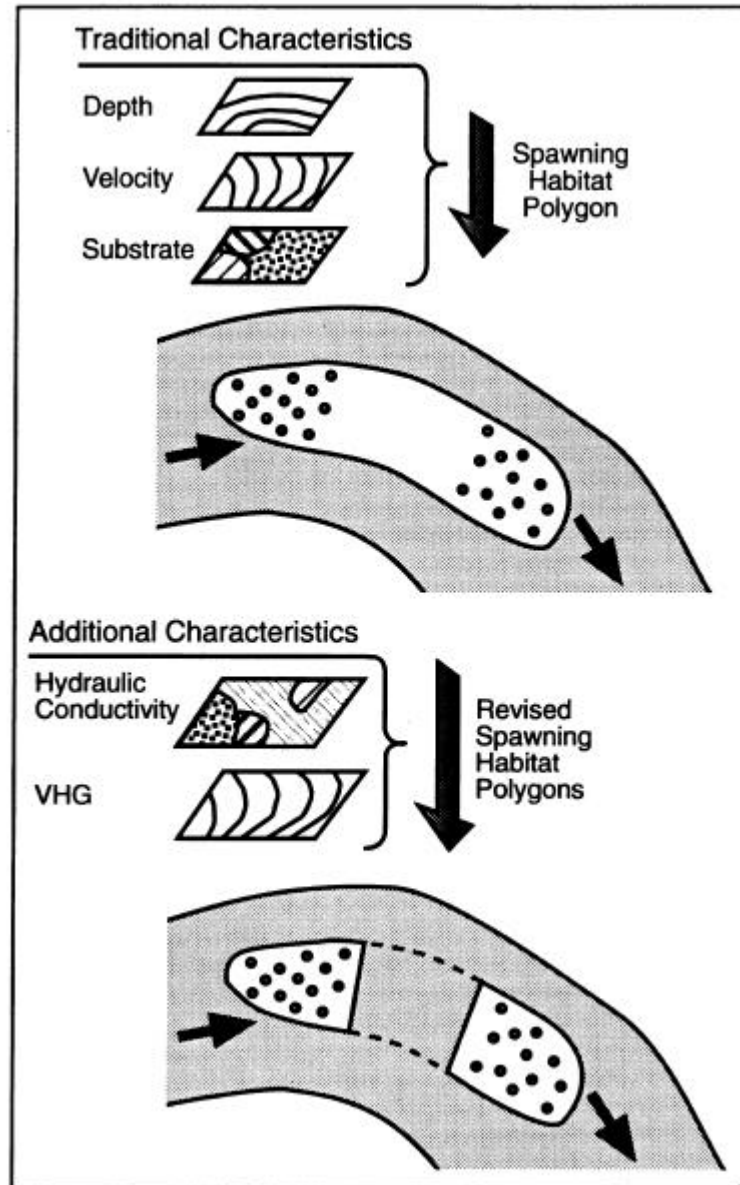


Figure 1.4. Spawning habitat polygons (SHPs) within a hypothetical salmon spawning area. Salmon redds are depicted by small circles. A large SHP is generated using data layers comprised of “traditional characteristics” (i.e., substrate, depth, and water velocity). The single SHP is refined into two smaller SHPs using data layers comprised of “additional characteristics”; in this example we have used hydraulic conductivity of the river bed sediment and the vertical hydraulic gradient (VHG) between the hyporheic zone and the river.

included. When “additional characteristics” (i.e., key hydraulic and hydrologic characteristics proposed here; Table 1.1) are incorporated into the model, the single large SHP is reduced into two smaller SHPs and more closely approximates the area actually used for spawning (Figure 1.4). Because this approach may result in more definitive predictions, we propose that researchers include general characteristics of hydrologic and bed processes in PHABSIM and future salmon spawning habitat models.

The characteristics proposed in our conceptual model are present in spawning habitat, yet are difficult to measure and quantify, and thus, typically ignored. We argue that this information can be empirically derived using recent tools developed for monitoring and modeling groundwater/surface water interactions in large rivers. For example, groundwater monitoring wells have been used to monitor the large-scale movement of subsurface flow and ecological connectivity within large river basins (Stanford and Gaufin 1974; Stanford and Ward 1988; Obrdlik et al. 1992). Piezometers have been used to monitor the intragravel flow within salmon spawning areas of small streams and rivers where installation costs and/or access for drill rigs prohibited the use of monitoring wells (Wickett 1954; Terhune 1958; Vaux 1962; Sheridan 1962; Hansen 1975), but their application to large rivers is limited (Geist et al. 1998). Estimates of hyporheic flux in large rivers may now be possible using recently developed remotely operated seepage meters (Cherkauer and McBride 1988; Taniguchi and Fukuo 1993). Rapid reconnaissance methods have also been developed to detect groundwater upwelling (Lee 1985), including areas in the Hanford Reach used for spawning by fall chinook salmon (Lee et al. 1997).

Improved predictions of usable fall chinook salmon spawning habitat can only be made if resource managers begin to consider the hyporheic zone in their studies of salmon spawning habitat. By measuring the difference in hydraulic head at various locations, and combining this information with the hydraulic properties of the hyporheic zone (i.e., horizontal and vertical conductivity, substrate porosity and permeability, transmissivity, and aquifer depth), general hyporheic gradients and flow rates can be modeled. Perhaps the simplest way to make these hydraulic measurements is with the use of piezometers installed into the riverbed within salmon spawning areas. The

following case study demonstrates one approach using piezometers that has been used to characterize the hyporheic zone within a salmon spawning area in a large river .

CASE STUDY: PRELIMINARY CHARACTERIZATION OF THE HYPORHEIC ZONE WITHIN FALL CHINOOK SALMON SPAWNING AREAS

Water depth, substrate size, lateral slope, and water velocity were not highly related to fall chinook salmon spawning sites in the Hanford Reach (D.R. Geist, unpublished data). For example, previous application of PHABSIM led to overestimates of fall chinook salmon spawning habitat in the Hanford Reach (Geist et al. 1997). PHABSIM estimated that over 50% of the habitat area at each of two study sites in the Reach should be utilized for spawning while actual use ranged from only 0 to 20%. It was hypothesized that fall chinook salmon were spawning near areas of hyporheic upwelling. Thus, piezometers (Geist et al. 1998) were installed into riverbed sediments (particle size = 2.5 to >30 cm diameter) in the wetted portion of the river channel within a major fall chinook salmon spawning area during 1995 and 1996. A portion of those piezometers were used in this case study and their locations are shown in Figure 1.5. The piezometers allowed us to determine the relative mix of groundwater and surface water in the hyporheic zone based on differences in electrical conductivity; Columbia River water at Hanford is normally around 125 to 150 $\mu\text{S}/\text{cm}$ compared to undiluted groundwater, which is normally around 300 to 500 $\mu\text{S}/\text{cm}$ (Peterson and Johnson 1992; Dresel et al. 1995). The piezometers also allowed us to determine the relative magnitude of upwelling and downwelling within the spawning area based on the vertical hydraulic gradient (VHG) between the river and the piezometers:

$$\text{VHG} = \frac{\Delta h}{L}$$

where Δh was the water surface elevation inside the piezometer minus the water surface elevation of the river and L was the distance below the river bed to the top of the piezometer perforations. A positive VHG indicates potential upwelling of hyporheic

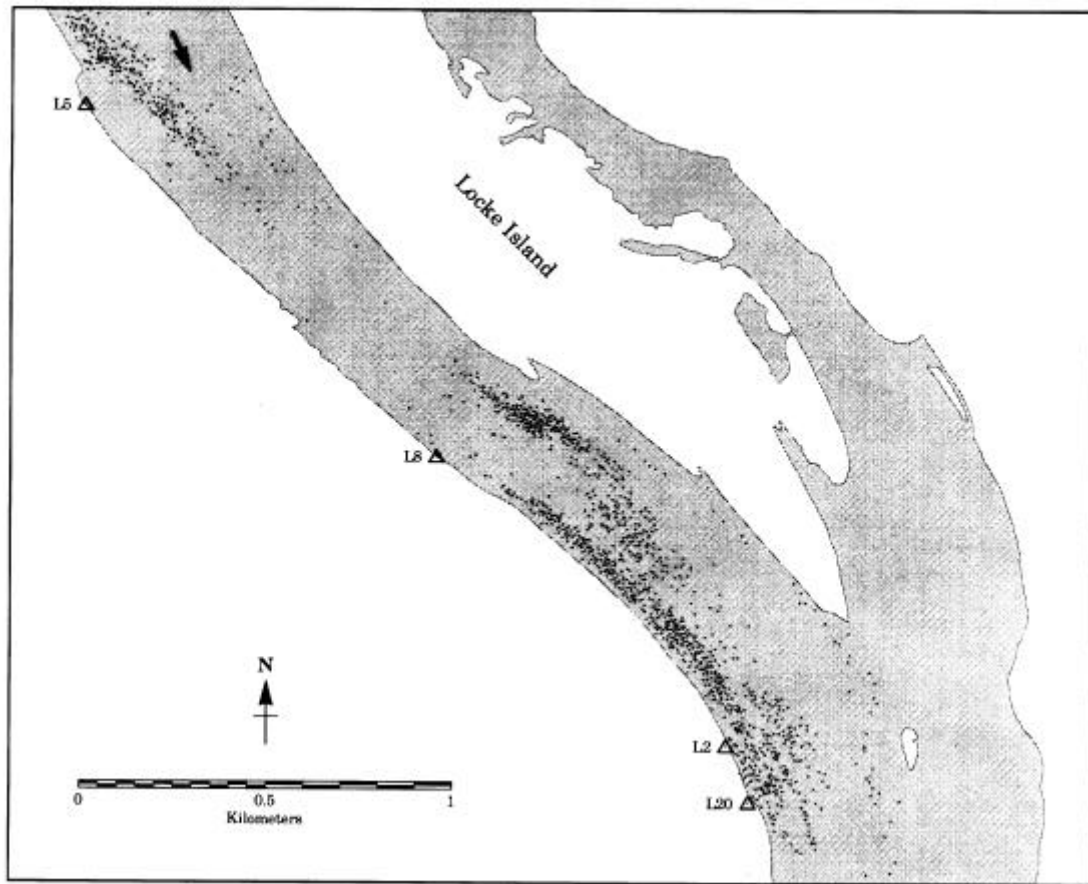


Figure 1.5. The location of four piezometers (L2, L5, L8, and L20) installed during 1995 and 1996 within the river channel within a major fall chinook salmon (*Oncorhynchus tshawytscha*) spawning area in the Hanford Reach of the Columbia River. Each dot represents an individual salmon nest (redd) that was digitized into a Geographic Information System from aerial photographs taken during 1995 at peak spawning (mid-November). Triangles depict piezometer location and the arrow indicates direction of river flow.

water into the river, while negative values indicate a potential for river water to downwell into the bed sediments (Dahm and Valett 1996).

Data collected from the piezometers clearly showed the hyporheic zone comprised varying proportions of groundwater and surface water as evidenced by the measurable differences in electrical conductivity within some of the piezometers but not others (Figure 1.6a). Further, the data revealed that a vertical hydraulic gradient existed between the hyporheic zone and the river (Figure 1.6b). The relative magnitude of the hyporheic discharge appeared to be a function of the river stage (Figure 1.6c) which fluctuates cyclically on a daily basis in response to discharge at a hydropower project (Priest Rapids Dam) located 39 km upstream.

These data suggest that the river banks, bars, and islands become saturated with river water as the river discharge and stage increase. Depending on substrate permeability, bed morphometry, channel configuration, and the relative rise in river level, river water downwells into the hyporheic zone due to high pressure created from increased water depth (negative VHGs; Figure 1.6c). Eventually the river and hyporheic zone come to a dynamic equilibrium; if the river discharge is reduced and the stage decreases, the pressure is released and water flows back into the river in the form of surface seeps or off-shore upwelling (positive VHGs; Figure 1.6c). Within the Hanford Reach, this alteration between upwelling and downwelling can occur several times per day, depending on the discharge pattern at Priest Rapids Dam. In unregulated rivers this phenomenon still occurs, but is protracted over a longer time period (days to months). Overall, the piezometer data provide evidence that the river at Hanford is connected to the groundwater within the hyporheic zone.

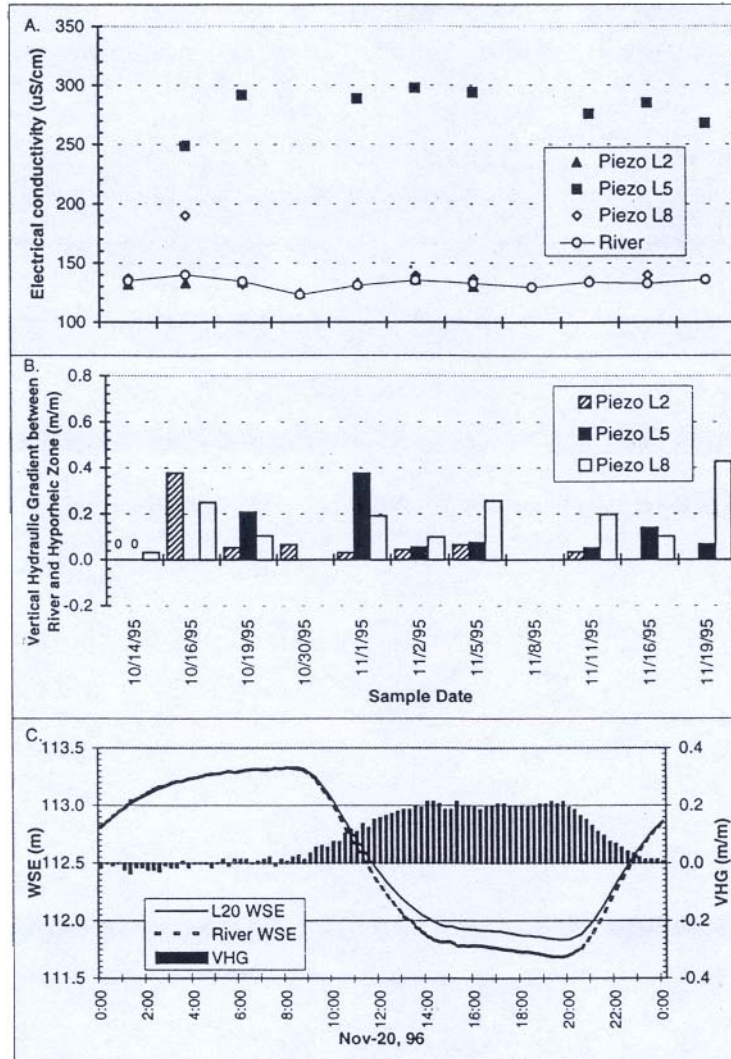


Figure 1.6. Data collected from a portion of piezometers placed in the hyporheic zone of the Hanford Reach of the Columbia River (see Figure 1.5 for salmon redd locations). (A) Measurements of electrical conductivity, and (B) vertical hydraulic gradient (VHG) from the river and three piezometers (L2, L5, and L8) during October and November, 1995. VHG of 0.0 (indicated by zeros) were recorded in piezometers L2 and L5 on 14-November; the absence of a vertical bar on subsequent dates indicates no measurements of elevation were made. The x-axis scale is the same for A and B. (C) Continuous measurements of water surface elevation (WSE) of the river and within piezometer L20 over a 24-hour period on 20 November, 1996. WSEs were used to calculate VHG over the same time-period. Measurements of electrical conductivity in L20 during November, 1996, were similar to electrical conductivity measurements taken in the river.

PREDICTION OF SALMON SPAWNING BASED ON MICRO-HABITAT CHARACTERISTICS

The predictive power of PHABSIM is restricted because it includes characteristics that are only measured at the micro-habitat scale. Often these characteristics differ considerably both between and within major spawning areas of similar stocks or races of chinook salmon (Table 1.2). For example, water depth over fall chinook salmon redds in the Hanford Reach has been reported to be from 0.3 to 9.0 m (Chapman et al. 1986; Swan 1989); substrate particle size ranges from 5 to 30.5 cm (Swan 1989); and near-bed velocity ranges from 0.4 to 2 m/sec (Chapman et al. 1986). Similar variability in physical habitat characteristics has been noted for chinook salmon spawning sites in the Snake River, Idaho (Groves 1993; Connor et al. 1994c; Groves and Chandler, in press), Kalama and Toutle rivers, Washington (Burner 1951), Nechako River, British Columbia (Neilson and Banford 1983; Shirvell 1989), and Kamchatka River, Russia (Vronskiy 1972; Vronskiy and Leman 1991).

Spawning habitat characteristics for chinook salmon in small rivers encompass a smaller range of possible conditions than those in the Columbia and Snake rivers because of differences in scale, i.e., the upper limits for depth and velocity are related to discharge (volume). For example, Smith (1973) recommended velocity criteria of 0.3 to 0.8 m/sec for spawning fall chinook salmon. Additionally, Bovee (1978) generated probability of use curves for substrate, depth, and velocity characteristics that ranged from 12 to 15 cm, 0.1 to 1.4 m, and 0.2 to 1.3 m/sec, respectively. These values are less than the upper limits reported in the Columbia and Snake rivers for fall chinook salmon redds.

Table 1.2. Summary of fall chinook salmon (*Oncorhynchus tshawytscha*) spawning characteristics in the mainstem Columbia River, major tributaries, and other streams in the Pacific Northwest. No data is indicated by —.

Location	Substrate size (cm)	Depth (m)	Velocity (m/sec)	Reference
Columbia River				
Upper	—	0.6-4.5	—	Chapman (1943)
Near Wells Dam	—	range 1.6-9.6 most 5.3-7.2	range 0.4-1.2 average 0.9	Giorgi (1992)
Hanford Reach	—	range 1.2-2.6 average 1.4	0.4-1.9 @ 2,000 m ³ /s 0.4-2.0 @ 3,400 m ³ /s	Chapman et al. (1983)
Hanford Reach	range 5-30 average 10-20	range 0.3-9.0 average 1.8-7.6	—	Swan et al. (1988), Swan (1989)
Not specified	—	0.2-2.0	0.8-1.1	Chambers (1955)
Columbia River tributaries				
Snake River	2.5-15	~1-2	~0.5-1.2	Connor et al. (1993)
Snake River	2.5-15.0	0.2-6.5 average 2.8	0.4-2.1 average 1.1	Groves and Chandler (in press)
Snake River	—	4.6-7.9	0.3-0.7	Dauble et al. (1995)
Kalama River	—	average 0.4	average 0.6	Burner (1951)
Toutle River	—	average 0.3	average 0.4	Burner (1951)
Other river systems				
Campbell River, B.C.	—	range 0.3-0.8 average 0.6	range 0.4-0.8 average 0.6	Hamilton and Buell (1976)
Nechako River, B.C.	—	—	0.15-1.0	Neilson and Banford (1983)
Oregon Streams	—	average 0.4	average 0.5	Smith (1973)
Unspecified streams	1.3-10.2	—	—	Bell (1986)

It is apparent that water depth, velocity, and substrate constrain where fall chinook salmon can successfully spawn. These limits are defined both by the size of the fish and the geomorphic characteristics of the river system. For example, chinook salmon will typically not spawn if their backs are out of the water (Bjornn and Reiser 1991). Thus, 30 cm is probably the minimum depth limit for successful spawning of an average-sized (i.e., 5 kg) fall chinook salmon female. Maximum spawning depth is limited by river channel dimensions and is also likely affected by water clarity. Visual cues related to mate recognition and substrate differentiation in the Hanford Reach would be reduced at depths greater than 4 m because this is the maximum depth of light penetration during the spawning period (Swan 1989).

Egg incubation success may be reduced at low water velocities, particularly where oxygen exchange is inadequate and metabolic wastes accumulate in the egg pocket (Chapman 1988). Thus, there is a selection disadvantage against fish that spawn in areas of low water velocity. Conversely, pre-spawning adult fall chinook salmon would be expected to avoid areas of very high water velocity because of costs to their available energy budget (Brett 1964, 1965). Maximum substrate size is limited by both the size of the fish (i.e., physical ability to dislodge substrate) and by water velocity, which may provide a “boost” to help in the excavation process (Kondolf and Wolman 1993). Minimum substrate size for spawning is critical in the sense that a high percentage of fines may smother eggs during incubation (Chapman 1988). In summary, the range of potential conditions accessible to fall chinook salmon for spawning appears quite broad.

The large data base available on physical characteristics of salmon redds, particularly for water velocity and depth, implies that spawning habitat of chinook salmon is well understood. However, the following example illustrates that major discrepancies exist between the amount and type of substrate thought to be available for spawning by fall chinook salmon and the habitat actually used.

CASE STUDY: SPAWNING SITE CHARACTERISTICS IN THE HANFORD REACH

In 1986, Swan et al. (1988) selected eight study sites in the Hanford Reach that were presumed to contain suitable spawning habitat for fall chinook salmon based on substrate, depth, and velocity data. Their objective was to survey these sites and to document redd locations prior to assessing potential impacts of channel dredging on fall chinook salmon spawning habitat. Although data were collected for other purposes, Swan et al. (1988) is the most definitive data set available on substrate types in major spawning areas of the Hanford Reach.

We capitalized on recent advances in GIS technology to evaluate substrate use and preference relative to available habitat. The study-site boundaries, substrate polygons, and redd locations were digitized from Swan et al. (1988) study site maps into our GIS (ArcInfo). For each study site, the area of each of five substrate types was calculated, and the number of salmon redds within the substrate type was enumerated. Substrate types included sand (<5 cm), gravel (5 to 10.2 cm), rubble (10.2 to 20.3 cm), rock (20.3 to 30.5 cm), and boulder/bedrock (>30.5 cm; Swan 1989). Spawning habitat used was defined as the proportion of the total number of redds within a study site found within each substrate type. Available spawning habitat was defined as the proportion of the five substrate types (based on area) within each study site. A preference index for a particular substrate was calculated by dividing the proportion of redds found within a substrate type by the proportion of habitat available within the same substrate type (Bovee 1986; Knapp and Vredenburg 1996). We then used linear regression analysis to test the hypothesis that the number of redds were related to the amount of preferred substrate. The dependent variable was the number of redds found within the preferred substrate at each study site, and the independent variable was the area of preferred substrate at each study site.

All study sites were located in areas of the Hanford Reach where fall chinook salmon spawn (Dauble and Watson 1997). We assumed that all the sites were equally available to returning adults. The number of fall chinook salmon that spawned in the

Hanford Reach during the study year (1986) was estimated to be 72,560, or approximately 40% higher than the average annual spawning population measured from 1982 to 1992 (Dauble and Watson 1997). Superimposition of redds was noted in some study sites (Swan et al. 1988; Swan 1989). Thus, we assumed the returning adult population was sufficient to allow full seeding of each of the eight study sites.

Fall chinook salmon spawned at five of the eight study sites in 1986 (Swan 1989). Sand was the least predominant substrate type at all sites and, with one exception, rubble and rock were the most predominant substrate types. Within the five study sites where spawning occurred, approximately 90% of the redds were found within the rubble and rock substrate types (Figure 1.7a) and indices suggested slight preference for these substrates (i.e., preference index values were 1.1 for both substrate types). Within the study sites where no spawning occurred, approximately 45% of the available substrate was classified as rubble and rock, the preferred substrate types (Figure 1.7b). However, regression analysis showed that the number of redds in the study sites were not related to the amount of available rubble and rock ($R = 0.07$, $df = 7$, $P = 0.870$).

We conclude that available spawning habitat (based only on substrate) at these sites did not provide a useful predictor of fall chinook salmon spawning potential. Swan (1989) concluded that water velocity and depth characteristics at these eight study sites were within the range thought suitable for spawning. More accurate predictions of spawning potential might have been possible if depth and/or velocity data were available for our analysis. However, our analysis demonstrated that superficial measures of spawning habitat quality, as measured at the micro-habitat scale, were limited in their ability to predict spawning habitat availability. We believe that other features of the river channel, such as hyporheic processes, must be considered.

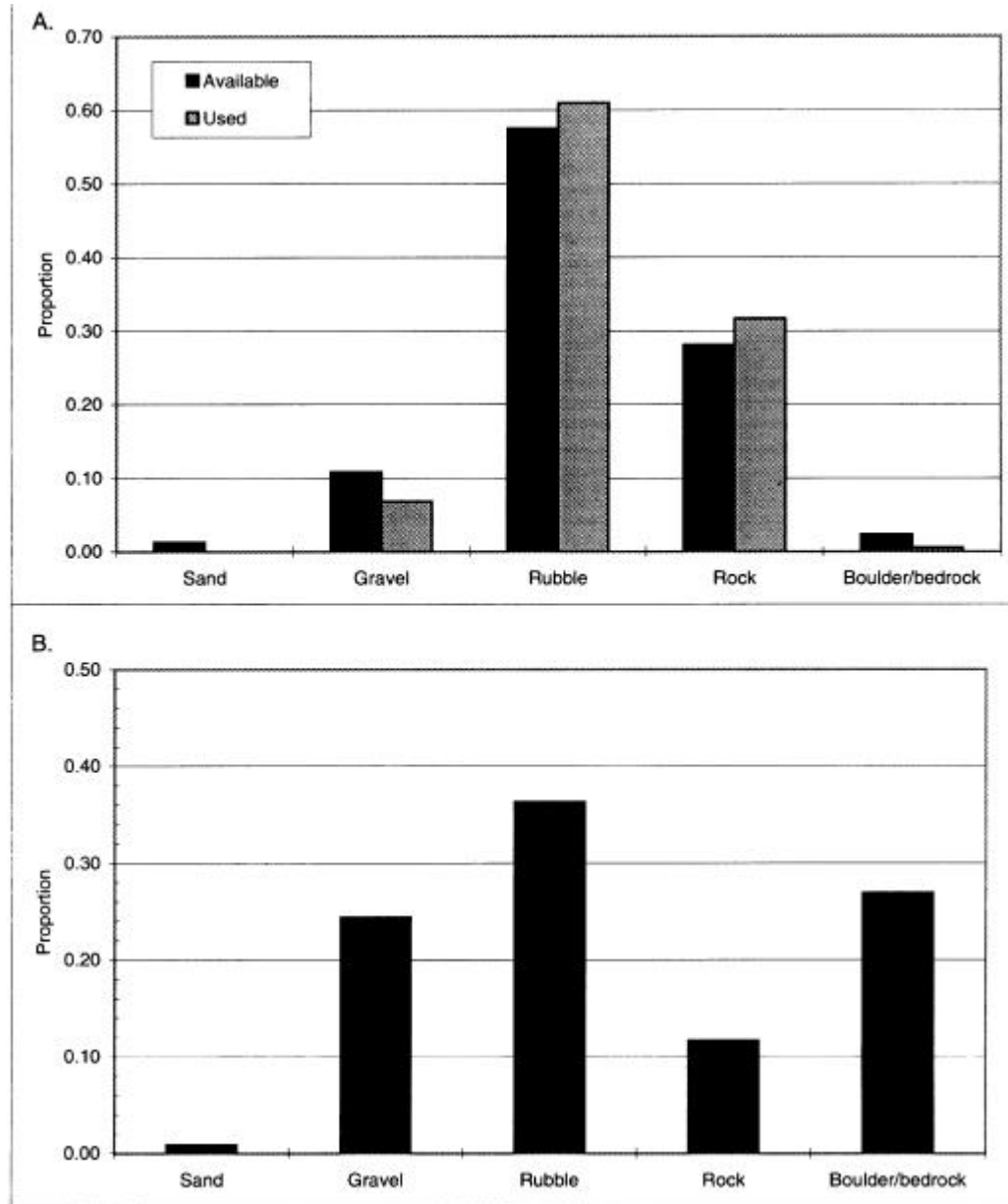


Figure 1.7. Analysis of substrate data from eight study sites in the Hanford Reach of the Columbia River (Swan et al. 1988). (A) The proportion of substrate available and substrate used within the five study sites where fall chinook salmon (*Oncorhynchus tshawytscha*) spawned. (B) Distribution of substrate size classes within the three study sites without fall chinook salmon redds.

HYPORHEIC ZONE AND SALMON SPAWNING HABITAT

Upwelling hyporheic flow is commonly associated with the spawning locations of salmonids, including brook trout (*Salvelinus fontinalis*) (Latta 1965; Curry et al. 1994; Curry and Noakes 1995), sockeye salmon (*O. nerka*) (Lorenz and Eiler 1989), chum salmon (*O. keta*) (Leman 1993), and rainbow trout (*O. mykiss*) (Sowden and Power 1985). Brook trout will preferentially spawn in sites of upwelling (Webster and Eiriksdottir 1976), often in areas with sandy and silty substrate, even when clean, uncompacted gravel containing no upwelling water is available nearby (Witzel and MacCrimmon 1983). Upwelling hyporheic flow was detected in nearly 60% of the sockeye spawning sites sampled in the mainstem areas of a glacial river where spawning habitat was limited because of siltation and substrate compaction (Lorenz and Eiler 1989). However, spawning brown trout (*Salmo trutta*) were shown to avoid areas of groundwater flow (Hansen 1975).

Provided that water quality is good and sufficiently oxygenated, upwelling areas would tend to improve survival of eggs and emergent fry by providing a stable egg incubation environment and increasing the water exchange around the egg pocket, thereby replenishing oxygen and removing waste (Becker et al. 1983; Bjornn and Reiser 1991; Curry et al. 1995). Owing to the tremendous heat store of the underlying sediments (Freeze and Cherry 1979), the average temperature of the hyporheic zone during the egg incubation period is often warmer than the river, which could ensure emergence at optimal times (Burger et al. 1985; Lorenz and Eiler 1989; Berman and Quinn 1991). Although it is clear that oxygen and temperature content of intragravel flow is important in salmonid egg survival, the importance of hyporheic upwelling to spawning site selection is not known. Gradients created by discharging hyporheic upwelling may provide chemical cues for homing (Hara 1982), changes in flow patterns that fish could sense, and/or temperature aberrations that would attract spawning fish; however, these hypotheses remain largely untested.

There are no definitive assessments of chinook salmon spawning in large rivers near hyporheic upwelling, rather, most information is circumstantial. For example, Chapman (1943) noted chinook salmon spawning in the mainstem Columbia River below Kettle Falls, Washington, and hypothesized that perhaps “seepage outlets [hyporheic upwelling] could explain the concentration of fish on the same spot when the greater part of the river was not in use.” Most spring chinook salmon spawning in the Entiat River, Washington, took place on gravel through which there was a flow of water as determined chemically (Burner 1951); however, hyporheic flow was not quantified. Chinook salmon spawned in the mainstem Kenai River, Alaska, at the tips of vegetated islands where “loose” mounds of clean gravel were available (Burger et al. 1985). Although groundwater hydraulics were not examined in the Kenai River study, the vegetated islands were suspected to facilitate gravel mound formation, which presumably increased subsurface flows and the incubation success of eggs. In the Kamchatka River, Russia, chinook salmon spawned in sections of the river that had a descending current of water (i.e., downwelling) in the substrate (Vronskiy and Leman 1991). Although most studies suggest that upwelling areas are more important than downwelling areas for spawning, this finding by Vronskiy and Leman suggests that intragravel flow is critical and whether it is upwelling or downwelling may not be as important.

The preference of salmon to spawn in locations with high intragravel flow may explain their tendency to aggregate in particular locations, while ignoring others that are superficially similar (Chapman 1943; Vronskiy and Leman 1991). These aggregations may explain why superimposition of redds, rather than colonization of new sites, appears to occur within some spawning areas. For example, Dauble and Watson (1990) noted that fall chinook salmon in the Hanford Reach exhibited an apparent high selectivity for certain locations, even though other sites with similar physical habitat characteristics were not used for spawning. This resulted in extensive overlapping of redds in the heavily used spawning areas. As previously noted, Swan (1989) also found that deep-water redds (i.e., >3 m depth and typically not visible during aerial surveys; Dauble and Watson 1990) commonly overlapped during the latter part of the spawning

season. Superimposition of chinook salmon redds also occurred in the Kamchatka River, where dense aggregations formed in selected locations while superficially similar areas remain unused (Vronskiy 1972). Although these studies did not confirm that the chinook salmon spawning areas were associated with the local emergence of hyporheic flow, they do suggest that specific, yet currently undescribed, geomorphic features of spawning areas may be critical to salmon reproduction.

The subsurface movement of water in the hyporheic corridor should be given more consideration. We believe that additional information on the location and quantity of hyporheic flux would better describe the connectivity between surface water and groundwater, and provide better predictions of available chinook salmon spawning habitat in large alluvial rivers. Improvements in techniques to sample and monitor the hyporheic zone in large rivers now makes this possible.

CONCLUSIONS

Considerable effort currently is underway to rebuild and enhance native salmon populations in the Pacific Northwest (NPPC 1994) and elsewhere on the west coast of the U.S. (USFWS 1991, 1996a, 1996b). Several salmonid stocks already have been listed under the Endangered Species Act (ESA), and additional petitions currently are being reviewed by federal resource management agencies. The ESA requires that recovery plans be developed for listed species, and most plans include the protection and restoration of spawning habitat. However, appropriate strategies cannot be successfully implemented without an adequate understanding of the critical elements within watersheds that determine where salmon spawn (Rondorf and Miller 1993; ISG 1996; Stanford et al. 1996). Although a large amount of information exists on the micro-habitat characteristics that define suitable salmon spawning areas, the predictive power of current habitat models is restricted because they are limited in scale. These models could be improved by incorporating the additional information proposed in our conceptual model that relates the physical characteristics of salmon spawning habitat to

hydraulic and geomorphic processes that occur within river systems, especially processes within the hyporheic zone. Improvements in our ability to predict salmon spawning habitat in large river systems will result in more realistic recovery potentials and aid in prioritization of restoration efforts.

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Chapter 2. Physical Factors Associated with Fall Chinook Salmon Redd Clusters at
Two Sites in the Hanford Reach, Columbia River

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ABSTRACT

Fall chinook salmon (*Oncorhynchus tshawytscha*) typically spawn in defined patches or “clusters” within the Hanford Reach of the Columbia River. Spatial point pattern analyses indicated that these clusters averaged approximately 10 hectares in area and their locations were consistent from 1994 to 1995. Redds were clustered when inter-redd distance exceeded 7 m, and the vast majority of redds were within 35 m of another redd. Additionally, there was strong evidence of a uniform distribution of redds within the clusters for short distances of 2 to 5 m. This behavior to spawn in clusters suggests fall chinook salmon selection for spawning habitat is highly selective. In fact, hydraulic characteristics of redd clusters were significantly different than the habitat surrounding them. Redd clusters were found to occur predominantly in areas of the river where water velocity was between 1 to 2 m/s, water depth was 2 to 4 m, and lateral slope of the riverbed was less than 4%. Less than 2% of the spawning occurred where water velocities were less than 1 m/s. In contrast, approximately 40% of the area outside redd clusters had water velocities less than 1 m/s. A logistic regression model determined that water velocity and lateral slope were the most significant predictors of redd cluster location. While the model accurately predicted the locations of the redd clusters, some unmeasured factors still accounted for a small percentage of the actual spawning site selection. Our results showed that salmon in the Hanford Reach were selecting spawning sites with quite specific attributes and that spawning habitat selection was finer-scale than previously observed. Better predictions of spawning habitat may be possible if spawning area-specific spawning characteristics are used.

INTRODUCTION

Spawning success of fall chinook salmon (*Oncorhynchus tshawytscha*) is highly dependent upon the physical characteristics of mainstem river habitats. Predicting the

Amount of salmonid spawning habitat is usually accomplished with habitat simulation models that are collectively known as the Physical Habitat Simulation system (PHABSIM; Milhous 1979; Stalnaker 1979). PHABSIM combines physical characteristics of the river channel (e.g., substrate and channel dimensions) into a hydraulic model that simulates how water surface elevation, depth, and velocity will change over a range of river discharges (Bovee and Bartholow 1995). A "map" of the river channel can be generated that provides a picture of what the physical characteristics of the river would look like at each simulated river discharge. To translate this picture into an estimate of salmon spawning habitat, spawning habitat suitability criteria are used to define the ranges of depths, velocities, and substrates that are utilized by spawning salmon. The standard procedure is to collect or use spawning habitat criteria that originated within the river of interest (Bovee 1995). The physical attributes of the river are compared against the habitat suitability criteria to determine the relative value of physical characteristics for spawning habitat

Numerous studies have attempted to characterize spawning habitat using PHABSIM, but accurate predictions of salmonid spawning are often difficult to achieve (Shirvell1989). For example, previous application of PHABSIM led to overestimates of fall chinook salmon spawning habitat in the Hanford Reach of the Columbia River (Geist et al. 1997). PHABSIM estimated that over 50% of the habitat area at each of two spawning areas (stretches of the river that were 3 to 5 km in length) in the Reach should have been utilized for spawning while actual use ranged from only 0 to 20%. We believe the disparity between PHABSIM predictions and actual use occurred because the spawning habitat criteria used in the habitat simulation models were measured at too coarse of a spatial scale (i.e., the Hanford Reach) and were not sufficiently specific to the spawning areas where the prediction were made. We hypothesized that PHABSIM estimates would have been improved had it incorporated fine-scaled habitat suitability criteria that were consistent with the pattern and scale of the fall chinook salmon spawning areas.

Our hypothesis is based on the concept that pattern and scale are intertwined, and the key to prediction and understanding of ecological systems lies in the elucidation of mechanisms underlying observed patterns (Levin 1992). At the coarsest scale, fall chinook salmon redds are typically aggregated in patches or “clusters” within the Hanford Reach (Geist and Dauble 1998). Superimposition of fall chinook salmon redds was common within some of these spawning clusters during years when adult returns were high (Swan 1989; Dauble and Watson 1997). This behavior indicated that adult fall chinook salmon selected redd sites within high-use spawning areas rather than seeking new spawning areas. Patchiness in the distribution of resources is fundamental to the way organisms exploit their environment and all ecological systems exhibit patchiness over a broad range of spatial scales (Levin 1992). The patchy redd distribution provides strong evidence that requirements of fall chinook salmon for spawning habitat are more specific than formerly believed.

A more complete understanding of the spatial scale at which salmon respond to physical habitat is critically important to help managers set priorities among planned restoration activities ranging from dam removal affecting large sections of river, to site-specific substrate modification. The wide range of spatial scales over which such restoration activities might take place suggests that it may be useful to examine scale-specific spawning patterns and determine the physical features that correlate with these patterns. Such a multi-scale analysis is possible in the Hanford Reach of the Columbia River where an average of 40,000 fall chinook salmon have returned annually to spawn over the period 1988 to 1992 (Dauble and Watson 1997).

The purpose of this paper was to determine the spatial scale at which salmon were selecting spawning locations based on standard spawning habitat characteristics measured within clusters of fall chinook salmon redds from two spawning areas in the Hanford Reach of the Columbia River. These were the same two areas where PHABSIM previously over-estimated spawning habitat (Geist et al. 1997). Spatial point pattern analysis was used to identify the spatial scale of regular and clustered patterns of redds. Hydraulic factors associated with the location of redd clusters were

tested using a logistic regression model. Our evaluation showed that spawning habitat criteria could be refined to better predict spawning habitat availability. These refinements may assist in salmon restoration efforts throughout the western United States.

Study Area

The Hanford Reach (Figure 2.1) is the last unimpounded section of the main-stem Columbia River in the United States and supports the largest population of fall chinook salmon in the Columbia River Basin (Dauble and Watson 1997). Upstream hydropower dams regulate flows through the Reach, and the mean daily discharge of the river varies seasonally from 1,140 to 7,070 m³/s. Because of rapid water releases during periods requiring peak power production at Priest Rapids Dam, water levels downstream of the dam commonly fluctuate up to 3 m per day. The Hanford Reach has no tributaries and no surface water inputs, except for irrigation returns and small seeps or springs.

In the Hanford Reach, the riverbed lies on top of a relatively thick sequence of fluvial, lacustrine, and glaciofluvial sediments composed of sand, gravel, and cobbles deposited during the cataclysmic Lake Missoula Floods (Reidel et al. 1994; Dresel et al. 1995). The depth of this material exceeds 5 m in some areas; most in-channel substrate is extremely stable and is thought to be sufficiently coarse to resist movement by flows as high as the regulated 100-yr frequency discharge (i.e., 12,500 m³/sec). Consequently, there has been little change in river platform and cross-sectional characteristics over the past century (Hall 1988).

Physical habitat data were collected at two sites in the Hanford Reach: Locke Island (Rkm 595-608) and Wooded Island (Rkm 560-563; Figure 2.1). Each study site was approximately 3.5 km in length, 300 to 400 m wide, and occurred in a braided channel. These sites have similar channel geomorphology, but very different redd densities. The average annual redd count from 1990 to 1995 was 513 redds (range 340

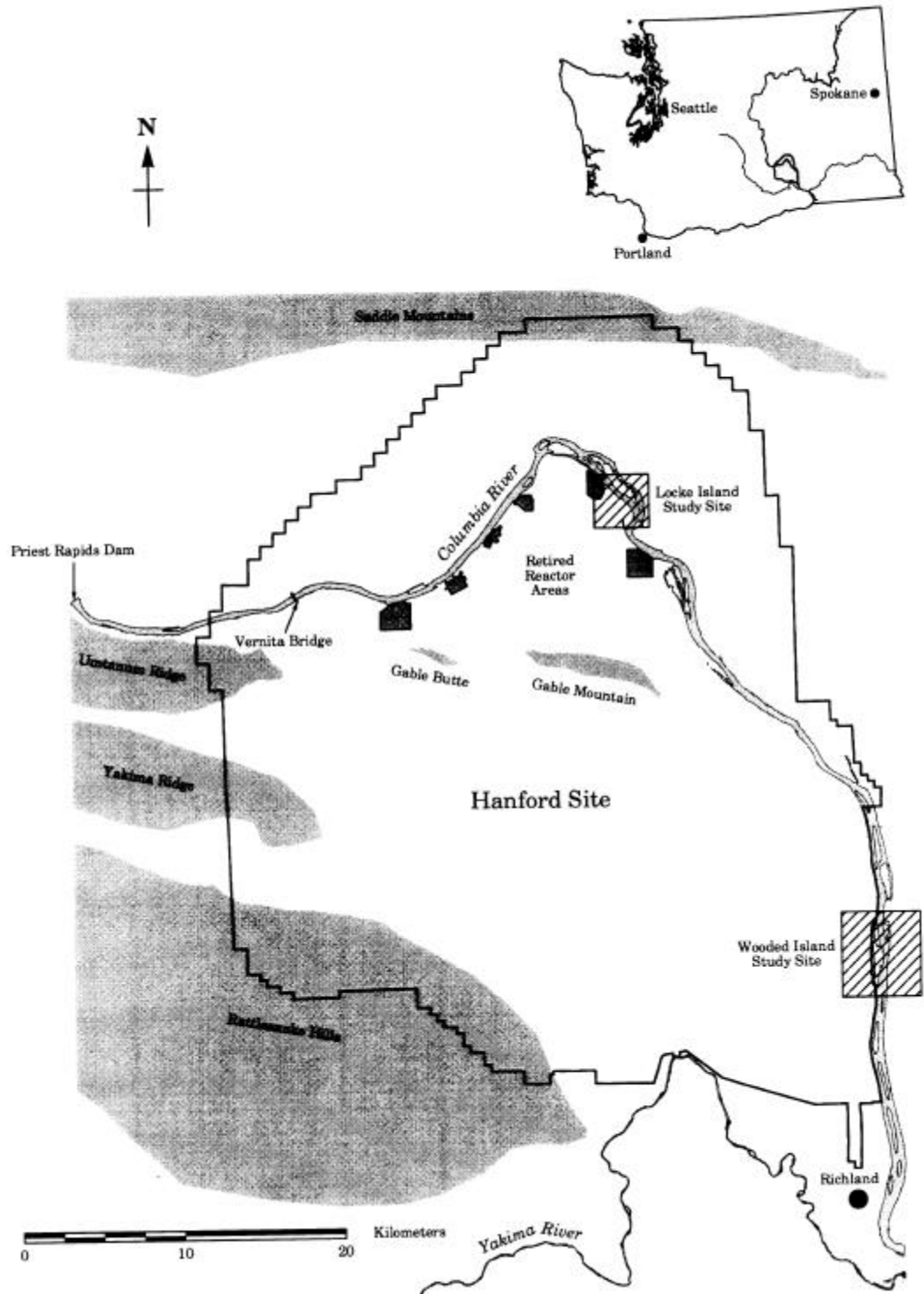


Figure 2.1. The Hanford Reach of the Columbia River showing the two study areas.

to 855 redds) and 10 redds (range 0 to 32 redds) for the Locke Island and Wooded Island study sites, respectively (Dauble and Watson 1997; D. Dauble, Pacific Northwest National Laboratory [PNNL], unpublished data).

METHODS

Redd Distribution

Fall chinook salmon redds were photographed at each site from a fixed-wing airplane flying approximately 600 m above the water surface (photographic scale of ~1:2,400). Flights occurred between the last week in October and the third week in November, or during the peak-spawning interval (Dauble and Watson 1990). One flight per week was made in 1994 (Locke Island site only) and 1995 (both sites). The center of each redd was digitized as a non-dimensional point and entered into an Arc-Info[®] Geographic Information System (GIS). The outer boundary of a sub-set of redds was measured to delineate redd size. Separate data layers were made by week; cumulative peak distributions are presented here (i.e., week 4; Figure 2.2). Because redds in water deeper than about 4 m were typically not visible from the air (Dauble and Watson 1990), additional redd surveys were conducted in 1995 using an underwater video camera. No additional redds were noted outside of the area of photographic record.

Hydraulic Habitat Data

Eight transects were set perpendicular to the flow, approximately 450 to 550 m apart, at each study site. River stage and river discharges were collected on three separate occasions (October 1995, June 1996, and July 1997) to establish stage-discharge relationships. Elevations were measured using a laser transit (Leitz/Sokkisha Set 2

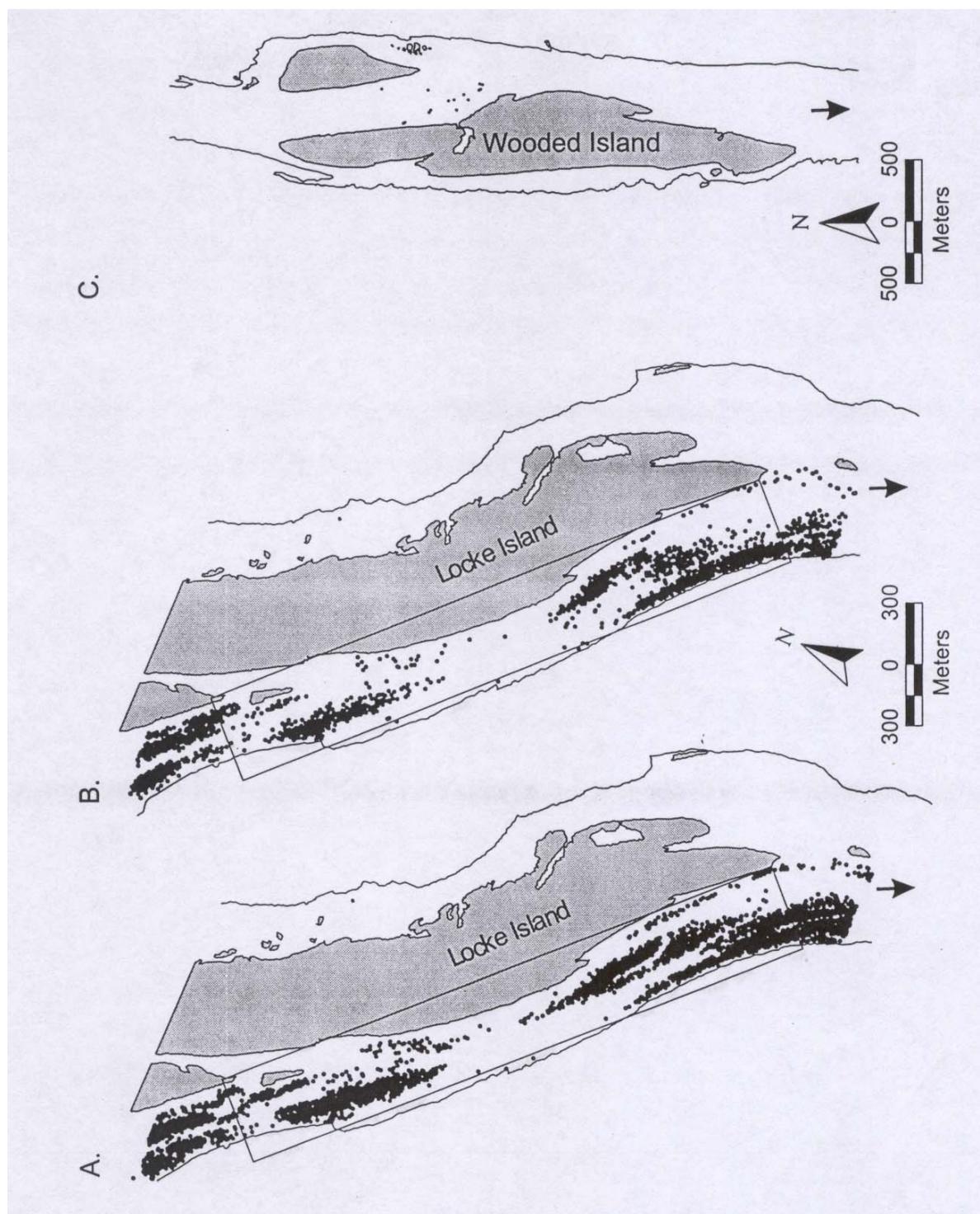


Figure 2.2 Distribution of fall chinook salmon (*Oncorhynchus tshawytscha*) redds following peak spawning at the two study sites: (A) Locke Island in 1994, (B) Locke Island in 1995, and (C) Wooded Island in 1995. The rectangular boundary where the spatial pattern analysis was completed is shown in A and B. In each panel, an arrow indicates flow direction of the river.

Electronic Total Station[®]), and discharge was measured using an acoustic Doppler current profiler (ADCP, model 600[®]). River discharge during the surveys ranged from 2,206 to 7,061 m³/sec.

During hydraulic calibration surveys conducted in October, 1995, mean water column velocities, channel elevations, and substrate sizes were collected at locations along each transect, which we refer to as habitat cells (Payne and Lapointe 1997) throughout the remainder of the text. Habitat cells were assumed to represent depth and velocity conditions of a hydraulically uniform area of river. We followed procedures of the Instream Flow Incremental Methodology (IFIM; Bovee 1982). The horizontal position (northing and easting) at each habitat cell was determined using the starting and ending coordinates collected by a surveyor and the distance between each measurement. Two passes were made on each transect with the ADCP; there were no statistical differences in discharge estimates between passes ($t = 0.006$, $P = 0.99$). Therefore, data from only the first pass were used in our analysis. The ADCP was used to measure water velocity when water depth was greater than 1 m. At water depths less than 1 m, channel elevation and water velocity (0.6 of the water depth) were measured using a standard top-set wading rod and a Marsh McBirney[®] flow meter. The water surface elevation was collected by surveyor concurrent with each velocity measurement. Lateral slope of the river bottom at each habitat cell was determined using cross-section elevations of the transects, and water depths collected with the ADCP. Average river discharge at Locke Island and Wooded Island study sites during these surveys was 1,950 and 2,462 m³/sec, respectively.

Substrate measurements were made on the hydraulic transects and on four additional transects that overlapped and bounded the spawning areas. Substrate images were collected using an underwater camera suspended about 40 cm above the riverbed (Garcia et al. 1994). At this depth, the size of the video image was 25 x 30 cm. Up to 20 substrate images were collected on each transect, or approximately 250 images at each study site. The location of substrate images was recorded using a Global Positioning System (GPS; Trimble Pro-Excel[®]). Each substrate image was later reviewed in

the laboratory and all individual substrate clasts within each image were measured (long axis diameter and surface area) and stored using a computer program (Optimus[®]). Each substrate image was assigned a dominant and sub-dominant size class (Brusven 1977; Groves and Chandler, in press) based on long-axis diameter. Dominant substrate was the most prevalent size class of substrate for each image as based on surface area; sub-dominant was the second-most common size class.

Defining Suitable Spawning Habitat

We indexed all hydraulic data to the same river discharge in order to compare the habitat available to the habitat used. The daily average discharge during peak spawning (2,400 m³/sec; Dauble and Watson 1997) was used as the spawning index flow and our depth and water velocity data were corrected to this value using an IFIM hydraulic simulation model (IFG-4; Milhous et al. 1984). Inputs to IFG-4 consisted of the stage-discharge data collected over the three discharges, and the depth and velocity data collected during the hydraulic calibration surveys. Output consisted of the simulated water column velocities and depths at each habitat cell. Velocity adjustment factors (VAF) were calculated by dividing the simulated velocity by the measured velocity (Bovee and Bartholow 1995). Simulations were suspect if the VAF was less than 0.1 or greater than 5.0; none of our simulations exceeded these criteria. Substrate and lateral slope of the river bottom were not corrected. We assumed these values would not change between the index flow and measured flows. Post-processing of the data resulted in 487 and 404 habitat cells at Wooded Island and Locke Island, respectively. Each habitat cell contained a simultaneous measurement of depth, substrate class (dominant and sub-dominant), mean water column velocity, and lateral slope.

The relationship between habitat cells and fall chinook salmon redd clusters was determined using the following approach (Figure 2.3). A buffer (r) was placed around the midpoint of each redd in the GIS to convert the point locations of individual redds into a measurement of area:

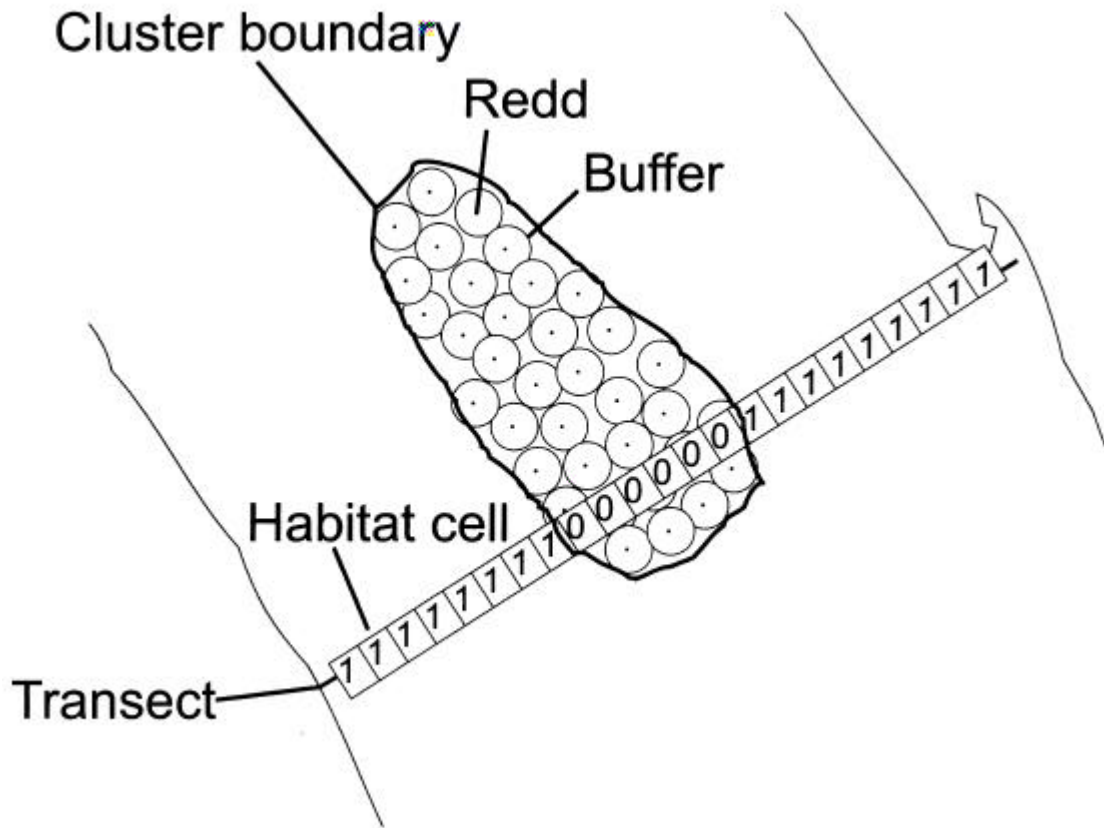


Figure 2.3. Schematic showing the process used to relate hypothetical habitat cells to fall chinook salmon (*Oncorhynchus tshawytscha*) redd clusters. Redd locations were digitized from aerial photographs into a Geographic Information System. A buffer was placed around individual redds that was based on the area measurements of a randomly selected sub-sample of redds in 1994 and 1995. A boundary was traced around the redd clusters using the definition provided in the text. Habitat cells (located along the transect) were coded as either suitable spawning habitat (inside the cluster = 0) or unsuitable (outside the cluster = 1).

$$r = \sqrt{\frac{A}{p}}$$

where A was the area occupied by individual fall chinook salmon redds in 1994 ($49.5 \pm 6.2 \text{ m}^2$) and 1995 ($66.5 \pm 11.3 \text{ m}^2$), and included inter-redd spacing (Geist et al. 1997). The buffer was estimated to be 4.3 m ($4.0 < r < 4.6$).

Once buffers were placed around individual redds (Figure 2.3), the outer boundaries of redd clusters were traced by hand in the GIS. Fall chinook salmon redd clusters were defined as patches of ≥ 25 redds with ≤ 50 m between individual redds. This definition was based on preliminary visual inspection of aerial photographs and experience gained during aerial spawner surveys. Each habitat cell on the transect was coded according to whether it fell inside (=0) or outside (=1) of a redd cluster. Habitat cells that fell inside redd clusters (i.e., coded 0) were assumed to be representative of “suitable” spawning habitat while those that fell outside the boundaries (i.e., coded 1) were assumed to be representative of “unsuitable” spawning habitat.

Spatial Pattern Analysis

The spatial pattern analysis was used to corroborate our definition of redd clusters. Two of the spatial data analysis techniques applied in this study required the use of a rectangular boundary for the study area, and the third was best suited to the analysis of rectangular map areas. For that reason, a reasonably straight section of the river within the Locke Island study site was chosen for the spatial data analysis (Figure 2.2). The location coordinates were transformed by rotation so that the long axis of the spatial study area was parallel to the longitudinal axis of the river. This provided a rectangular boundary 425 m wide and 2,850 m long. The aerial photographs depicted 1,947 redds in that area during 1994 (Figure 2.2a) and 1,074 during 1995 (Figure 2.2b).

Three methods were used to examine the spatial distribution of the redds at the Locke Island study site in 1994 and 1995: (1) refined nearest neighbor analysis,

(2) Ripley's $K(d)$ analysis, and (3) indicator variogram analysis. Refined nearest neighbor analysis (Boots and Getis 1988) uses the cumulative distribution function $F(d)$, to describe the probability that the nearest neighbor to a redd is within a given distance d . For a random spatial distribution generated by a Poisson process, the expected cumulative distribution function is:

$$F(d) = 1 - e^{-\lambda \pi d^2}, d \geq 0$$

where λ is the intensity of the points within the area, estimated by $\lambda = n/A$ for n points in area A . The empirical cumulative distribution of distances can be calculated from the data set for each distance d , and compared with the expected value for that distance.

Ripley's $K(d)$ analysis (Boots and Getis 1988) was used to examine the distance d , from each point to all other points (i.e., interevent distances). The cumulative distribution function of the interevent distance for a random process is given by:

$$K(d) = \frac{1}{n} \sum_{i=1}^n \sum_{j=1}^n \delta_{ij}(d), \text{ for } i \neq j$$

where $\delta_{ij}(d)$ equals 1 if $d_{ij} \leq d$ and 0 if $d_{ij} > d$, and d_{ij} is the distance between point i and point j . $K(d)$ is defined as the expected number of points within a distance d of a given point. The empirical cumulative distribution function of interevent distances was calculated for the data and compared with the expected distribution under a Poisson process.

The software used to perform the refined nearest neighbor and Ripley's K analysis (M. Moeur, US Forest Service, software available via anonymous FTP from forest.moscowfsl.wsu.edu/trees) includes edge correction to correct for bias when the distance from a point to its nearest neighbor is greater than its distance to the boundary of the study area (Boots and Getis 1988; Moeur 1993). The software generates a Monte Carlo confidence envelope around the expected value for each distance d . The

empirical cumulative distribution determined from the data is compared with the confidence envelope for each d : if the proportion of the nearest neighbors less than distance d is outside the confidence envelope, then the hypothesis that the spatial pattern of the data points resulted from a random process is rejected at the 95% confidence level. The direction of the deviation above or below the confidence envelope indicates whether the non-uniform pattern tended toward a uniform or clustered distribution, respectively. For both the refined nearest neighbor and Ripley's $K(d)$ analyses, 100 realizations were generated for the Monte Carlo simulations (Boots and Getis 1988). The maximum distance for which the empirical cumulative distributions should be calculated is half the length of the smaller dimension of the bounding box (Moeur 1993), so distances were evaluated up to a maximum of 215 m, in 1-m increments.

The third tool used for spatial pattern analysis was variogram analysis (Isaaks and Srivastava 1989; Rossi et al. 1992). The two spatial point pattern techniques discussed above focus on the distances between pairs of points. The variogram, on the other hand, measures the average difference between pairs of points as a function of the distance between the points in each pair. The technique has been used in ecology, where it is frequently called paired-quadrat variance (Ludwig and Reynolds 1988). If a variable possesses spatial continuity or autocorrelation, then calculation of the variogram will show that pairs of points separated by short distances will have smaller average differences than pairs of points that are separated by large distances. Fitting a mathematical model to the shape of the variogram can be used to infer the range over which spatial autocorrelation is present (Isaaks and Srivastava 1989). The type of variogram used in this study was the indicator variogram, which can be used to determine the spatial continuity of binary classes of data (Isaaks and Srivastava 1989).

For the variogram analysis of the redd data, the spatial study area of the Locke Island site (Figure 2.2) was partitioned into cells 20 m on a side. An indicator transform of the redd data was used for the variogram analysis, so that a value of 1 was assigned to a cell if it contained a redd, and a zero if it didn't. A 20-m cell size was chosen for the indicator variogram analysis because that was the minimum cell size that resulted in

at least one redd per cell for most cells within the redd clusters. This was important because the objective of the indicator variogram analysis was to detect spatial continuity of the redd clusters at spatial scales consistent with the definition of cluster size, rather than detecting the blank spaces within redd clusters. The redd clusters were defined using the procedure outlined above (groups of at least 25 redds separated from the nearest redd by less than 50 m). Directional indicator variograms (Isaaks and Srivastava 1989) were used to assess if spatial continuity (i.e., autocorrelation) existed in the spatial distribution of cells occupied by at least one redd both parallel and perpendicular to the longitudinal axis of the river. The range of spatial continuity of the redd-occupied cells in each direction was determined by fitting spherical variogram models to the experimental variograms (Isaaks and Srivastava 1989). We interpreted the variogram ranges parallel and perpendicular to the long axis of the river as an estimate of the average dimensions of the redd clusters in those directions.

The clusters identified by the spatial point pattern analyses appeared to be persistent between years. A contingency table and χ^2 test were used to test the hypothesis that occupation of a 20-m cell by a salmon redd in 1995 was independent of occupancy in 1994.

Logistic Regression Model

Logistic regression, based on negative log likelihood (Hosmer and Lemeshow 1989), was used to predict whether suitable spawning habitat was related to depth, substrate, velocity, or lateral slope. All variables were treated as continuous variables with the exception of dominant and sub-dominant substrate, which were treated as discrete factors with six levels based on substrate diameter: 1 = <0.63 cm; 2 = 0.63 to 2.54 cm; 3 = 2.55 to 5.08 cm; 4 = 5.09 to 7.62 cm; 5 = 7.63 to 15.20 cm; 6 = >15.20 cm.

A stepwise process with addition of variables was used to attain the final model (Hosmer and Lemeshow 1989). First, univariate analysis of each variable was conducted, then those variables with a P-value <0.25 were included in the multivariate

analysis. Variables were added to the model successively if they improved model fit based on a likelihood ratio test (G; defined as twice the difference in negative log likelihood between the two models with a $p < 0.05$). Once relevant variables were selected, all combinations of interaction terms were investigated and, again, those interaction terms that met the log-likelihood criterion were included in the final model. The odds ratio (Hosmer and Lemeshow 1989) was used to describe the relationship between independent variables and the response variable (suitable habitat).

The logistic regression model and parameters were derived from 1994 data from Locke Island only. Model predictions were then compared to observations made in 1995 from Locke and Wooded islands. The use of the model at the Wooded Island site was deemed appropriate because of the similarity of the habitat characteristics between the two sites (Figure 2.4).

The probability that a habitat cell would be suitable for spawning ($\pi(x)$) was:

$$p(x) = \frac{e^{g(x)}}{1 + e^{g(x)}}$$

where $g(x)$ was the linear combination of parameter estimates obtained from the logistic regression (Hosmer and Lemeshow 1989). A habitat cell was predicted to be suitable for fall chinook salmon spawning if the probability was greater than 50%. A chi-square test on a contingency table was used to compare the predicted designation of the habitat cell with the actual use by spawning salmon.

RESULTS

Redd Distribution

There were large differences in the number of redds between Locke Island and Wooded Island (Figure 2.2). Only 15 redds were recorded on the aerial photographs in

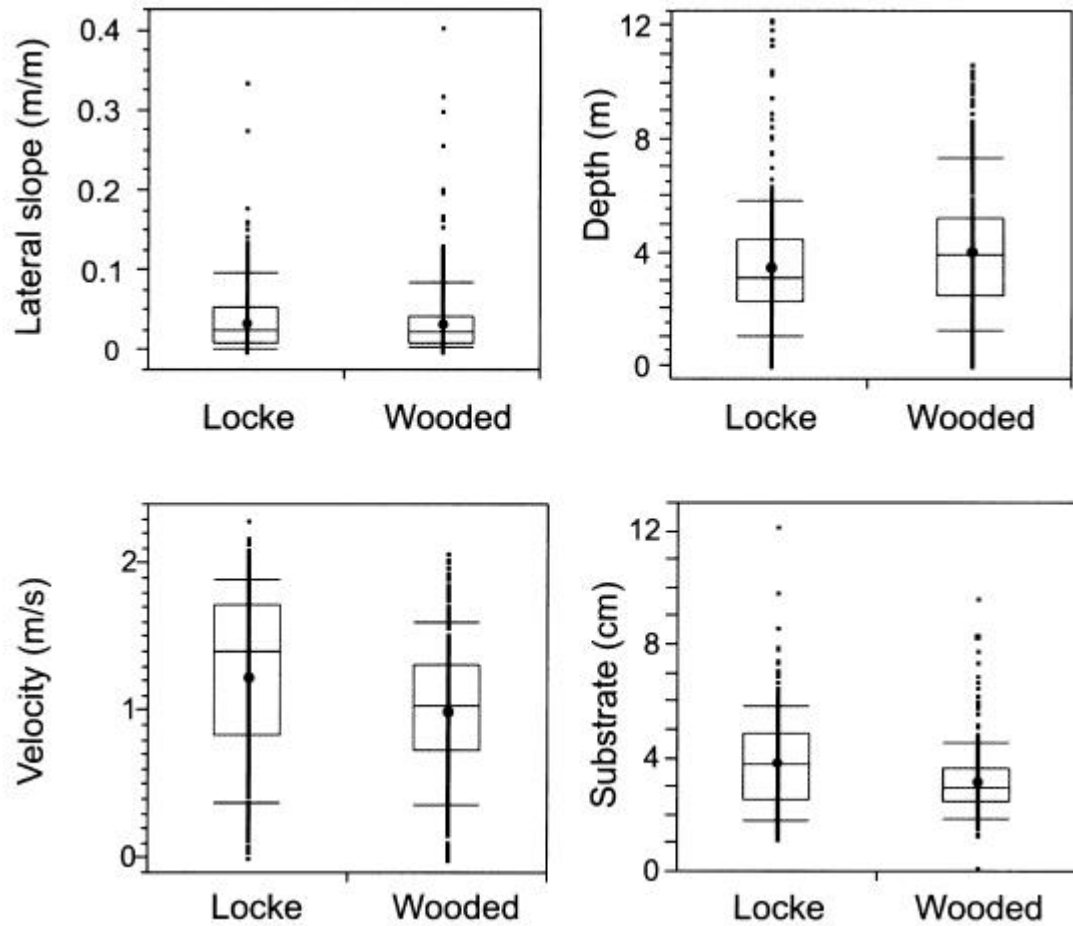


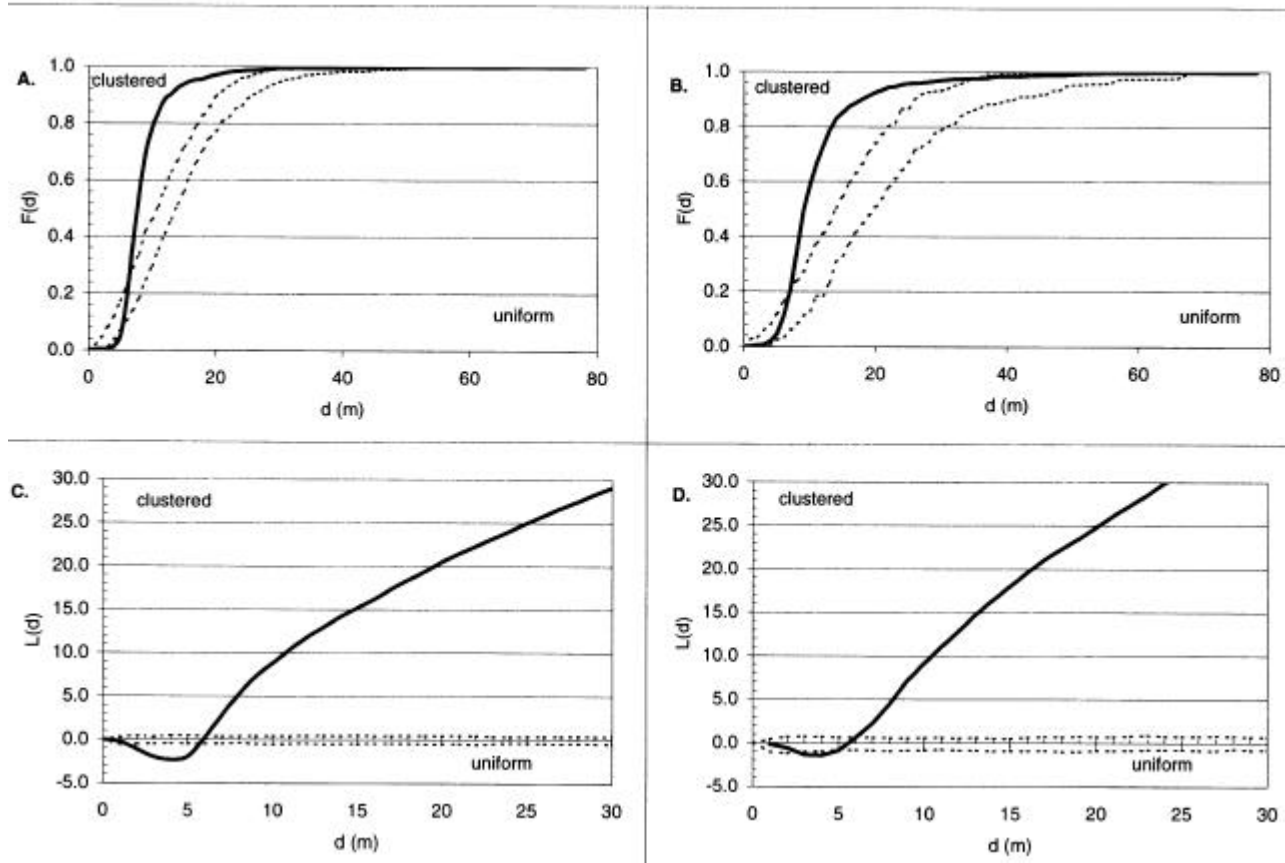
Figure 2.4. Quantile box-plots of lateral slope, water depth, water velocity, and substrate size (long axis diameter) at Locke Island and Wooded Island. The box shows the group median as a line across the middle and the quartiles (25th and 75th percentiles) as it ends. The 10th and 90th quantiles are shown as lines above and below the box. The mean is represented as a dot within the box.

the Wooded Island site in 1995; whereas, redd numbers at the Locke Island site were 2,481 in 1994 and 1,359 in 1995. Average redd density (total redd numbers) within the rectangular box at Locke Island where the spatial pattern analysis was completed (Figure 2.2) was 16.1 (1,947) and 8.9 (1,074) redds/hectare in 1994 and 1995, respectively. This result indicated a 55% reduction in the number of redds from 1994 to 1995.

The spatial point patterns of salmon redds at Locke Island in 1994 and 1995 were significantly non-random and clustered, as indicated by both the refined nearest neighbor and Ripley's $K(d)$ analyses (Figure 2.5). The nearest neighbor analyses indicated clustering by positive deviations above the Monte Carlo confidence envelope for distances greater than 7 m, and showed that the vast majority of redds were located within 30 m of another redd ($> 99\%$ for 1994 and $> 97\%$ for 1995; Figure 2.5a,b). Inter-redd distances greater than 7 m were shown to be significantly non-random by the Ripley's $K(d)$ analysis, and also consistent with an interpretation of clustering (Figure 2.5c,d).

The variogram analysis also confirmed that redds were clustered as indicated by the markedly lower variogram values near the origin (Figure 2.6). The variogram range in the longitudinal direction showed that the average length of redd clusters within the Locke Island study area in 1994 and 1995 was 800 m (Figure 2.6a). The directional variograms calculated perpendicular to the long axis of the river indicated that average width of the redd clusters was only about 120 m (Figure 2.6b). The difference in where the variograms level off each year (i.e., the sill) is caused by the difference in the proportion of cells that were occupied by redds in the two years, with 1994 having a much higher proportion of occupied cells.

The refined nearest neighbor and Ripley's $K(d)$ analyses also indicated the presence of a non-random (uniform) distribution of redds for short distances of 2 to 5 m (Figure 2.5). At those distances, however, the empirical distributions measured from the data fell below the confidence envelopes, indicating that those redds were more uniformly distributed than would be expected for a random process.



5. Spatial point pattern analysis of fall chinook salmon (*Oncorhynchus tshawytscha*) redds at Locke Island. Refined nearest neighbor results ($F(d)$) on redds in (A) 1994 and (B) 1995, and Ripley's $K(d)$ results ($L(d)$) in (C) 1994 and (D) 1995. The solid lines for $F(d)$ in A and B represent a cumulative histogram of the nearest neighbor distances calculated from the data, while the solid lines in C & D represent a linearized transformation ($L(d)$) of the calculated $K(d)$ statistic for the interevent distances. The dashed line in each panel represents the upper and lower boundaries of the 95% confidence envelope of 100 Monte Carlo simulations. Deviation of the empirical distributions (solid lines) for either technique above or below the confidence envelope indicates redd distributions that are clustered or uniform, respectively. Random redd distribution is indicated when the solid line is contained within the confidence envelope.

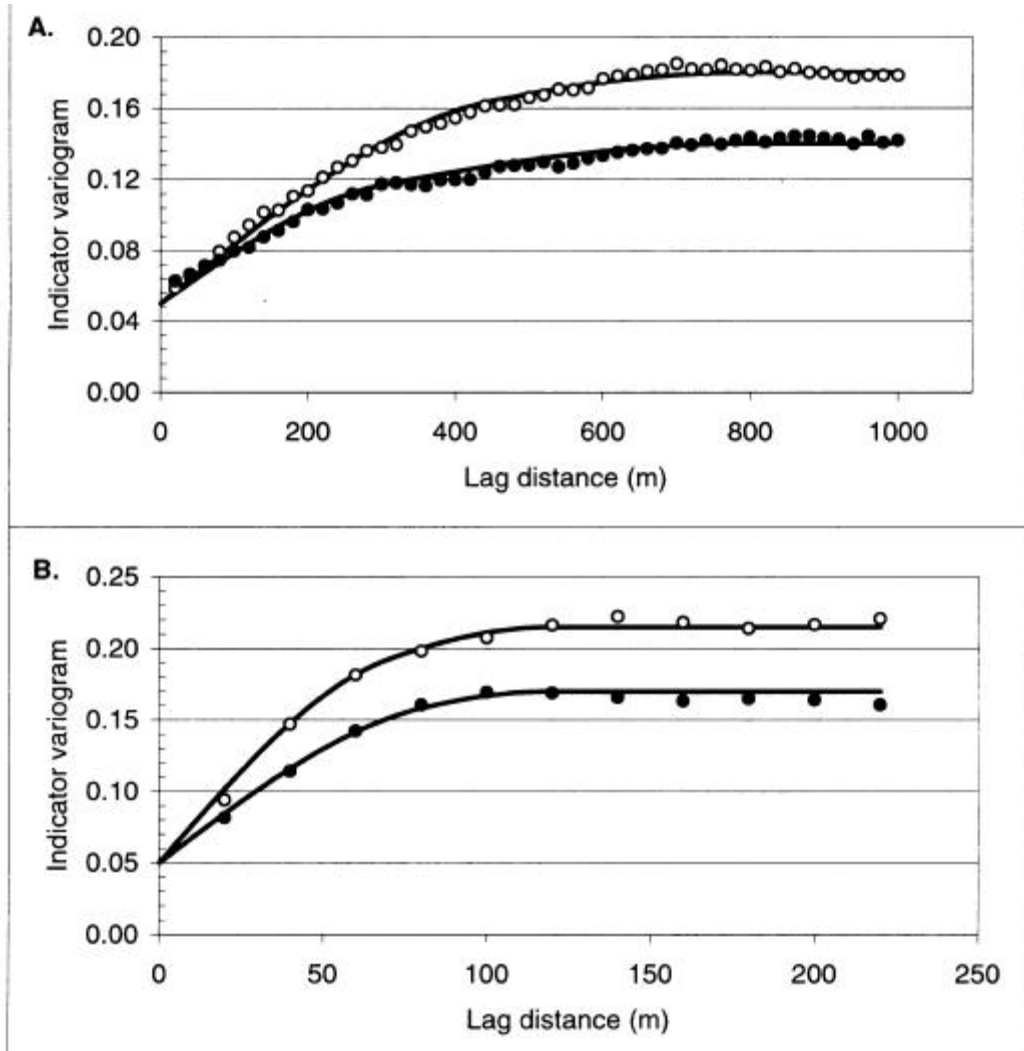


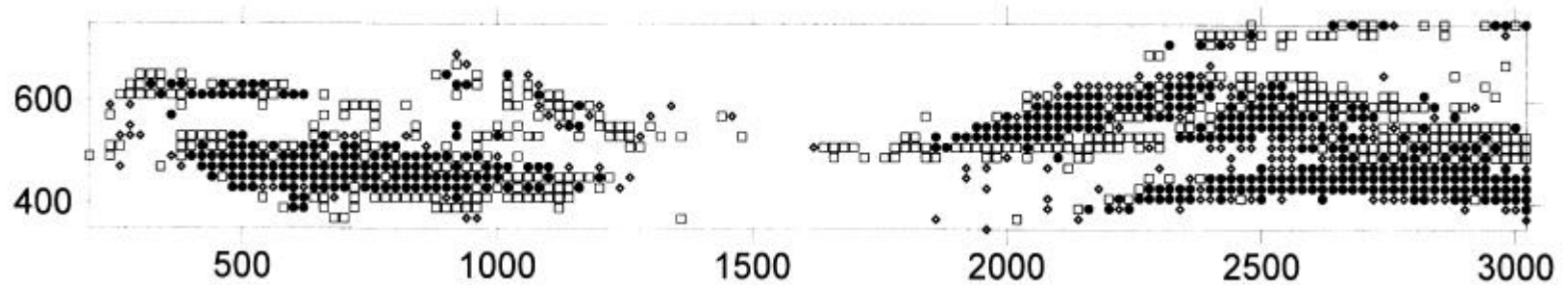
Figure 2.6. Indicator variogram analysis of fall chinook salmon (*Oncorhynchus tshawytscha*) redds at Locke Island in the (A) longitudinal and (B) lateral directions. In both panels, the empirical variograms for 1994 (open circles) and 1995 (filled circles) are shown along with the variogram model for each year and each direction (solid lines).

The locations where fall chinook spawned were extremely consistent from 1994 to 1995 (Figure 2.7). The number of cells occupied in 1994 that were reoccupied in 1995 was approximately 3 times the expected value under random conditions ($P < 0.001$; Table 2.1). The majority of the differences that occurred were the results of cells that were occupied in 1994, but not occupied in 1995 (i.e., square symbols in Figure 2.7). Some reduction in re-occupancy was expected because there were only 55% as many redds in the study area in 1995 as there were in 1994. But, 77% of the cells occupied by redds in 1995 were also occupied by redds in 1994. A test of the contingency table was highly significant ($\chi^2 = 883$, $df = 1$), indicating a low probability (<0.001) that the reoccupation occurred by chance alone.

Hydraulic Habitat Data

Although fall chinook salmon appeared to spawn within a specific area at Wooded Island (Figure 2.2), there were an insufficient number of redds to meet our definition of a redd cluster. Thus, none of the habitat cells along transects at Wooded Island were coded as suitable spawning habitat. In contrast, at the Locke Island site 85 and 86 of 404 habitat cells were coded as suitable spawning habitat in 1994 and 1995, respectively.

In both years, the habitat cells within redd clusters at the Locke Island study site had significantly lower lateral slope and significantly higher velocities than habitat cells outside redd clusters (Figure 2.8a,b). Spawning habitat inside redd clusters contained significantly more dominant substrate between 5.1 and 15.2 cm and subdominant substrate between 2.5 and 7.6 cm than habitat outside redd clusters (Figure 2.8c). There



7. The distribution of fall chinook salmon (*Oncorhynchus tshawytscha*) redds in 1994 and 1995 within a 425 x 2,850 m area at the Locke Island study site. Depending on the distribution of redds, a cell (20 x 20 m) was coded in one of four ways: no symbol = no redds in 1994 and no redds in 1995; square = redds present in 1994 but not in 1995; diamond = no redds present in 1994 but redds present in 1995; and filled circles = redds present at that location in both years.

Table 2.1. Contingency table showing recurrence interval for redds in 1994 and 1995.

		1995		
		Redd absent	Redd present	Totals
1994	Redd absent	2,048	130	2,178
	Redd present	370	434	804
	Totals	2,418	564	2,982

was no significant difference in depth inside or outside redd clusters, although habitat cells in redd clusters tended to have shallow water (Figure 2.8d). Approximately 70% of the habitat cells inside redd clusters were characterized by water velocity between 1 to 2 m/s, lateral slope <4%, and water depth 2 to 4 m (Table 2.2). Less than 2% of the habitat cells inside redd clusters contained water velocities <1 m/s. In contrast, ~40% of the habitat cells outside redd clusters were characterized by water velocities <1 m/s (Table 2.2).

Results from the univariate model analysis suggested all variables should initially be included in the multivariate model (i.e., $P < 0.25$; Hosmer and Lemeshow 1989). Although there were differences in substrate inside and outside redd clusters, this parameter was not a significant predictor in the multivariate logistic regression model ($P = 0.24$ for dominant and $P = 0.10$ for subdominant substrate). Velocity was the most important variable in determining spawning habitat utilization followed by the interaction term between depth and velocity and lateral slope. Depth by itself was insignificant. The best linear combination of parameter estimates obtained from the logistic regression analysis ($g(x)$) was:

$$g(x) = -12.58 + (13.68 * v) + (0.29 * d) - (23.17 * s) - (1.73 * [v*d])$$

where v = velocity (m/s), d = water depth (m), and s = lateral slope (m/m). An increase in velocity of 0.1 m/s resulted in over a three-fold increase in the probability that the habitat cell would be suitable spawning habitat (Table 2.3). Conversely, a decrease in lateral slope of approximately 1% resulted in a 25% increase in the probability of the site being utilized for spawning.

Table 2.2. Distribution (percentages) of habitat cells inside and outside fall chinook salmon (*Oncorhynchus tshawytscha*) redd clusters by habitat category (i.e., water velocity, lateral slope, and water depth), Locke Island, Hanford Reach, Columbia River.

Year	Lateral slope	Water velocity (m/s)	Inside redd clusters			Outside redd clusters		
			Depth (m)			Depth (m)		
			0-2	2-4	>4	0-2	2-4	>4
1994	0-2%	0-1	-	-	-	4.7	11.0	-
		1-2	7.1	48.2	10.6	-	8.2	12.9
		>2	-	1.2	3.5	-	-	2.2
	2-4%	0-1	-	-	-	3.8	2.8	-
		1-2	-	17.6	1.2	-	7.2	6.3
		>2	-	-	-	-	-	-
	>4%	0-1	-	-	-	10.7	5.0	4.1
		1-2	2.4	8.2	-	-	8.8	10.7
		>2	-	-	-	-	-	-
1995	0-2%	0-1	-	-	-	4.7	11.0	-
		1-2	5.8	54.7	3.5	-	6.3	14.8
		>2	-	1.2	1.2	-	-	2.8
	2-4%	0-1	-	-	-	3.8	2.8	-
		1-2	-	15.1	3.5	-	7.9	5.7
		>2	-	-	-	-	-	-
	>4%	0-1	-	1.2	-	10.7	4.7	4.1
		1-2	1.2	8.1	4.7	-	8.8	9.4
		>2	-	-	-	-	-	-

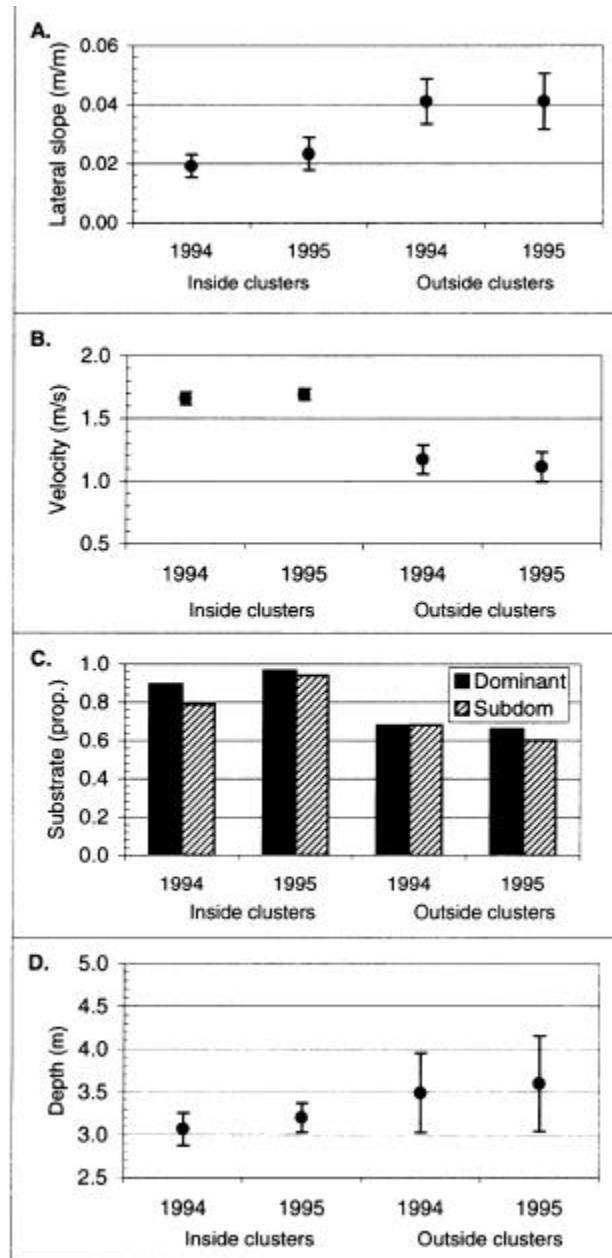


Figure 2.8. Average (A) lateral slope, (B) water column velocity, (C) dominant (5.1 to 15.1 cm) and subdominant (2.5 to 7.6 cm) substrate, and (D) water depth inside and outside redd clusters within the Locke Island study site during 1994 and 1995. Bars above and below the points represent the 95% confidence interval of the mean.

Once constructed using the Locke Island data from 1994, the model was used to explain the distribution of suitable spawning habitat at Locke Island and Wooded Island in 1995. At Locke Island, the model explained a significant proportion of the variance in habitat cell designation ($\chi^2 = 145.7$; $df = 403$; $P < 0.0001$) with approximately 86% of the habitat cells correctly predicted as either suitable (probability $> 50\%$) or unsuitable spawning habitat (Table 2.4). Even though the percentage of correct predictions was high at Locke Island, over a third (Table 2.4 – $0.10/0.27 = 0.37$) of the sites predicted to be utilized for spawning were not (i.e., errors of commission). Sites where errors of commission occurred contained similar physical features as those sites where spawning occurred, i.e., mean lateral slope, depth, and velocity of 2.6%, 3.0 m, and 1.7 m/s, respectively. Roughly 20% of spawning at Locke Island (Table 2.4 – $0.04/0.21 = 0.19$) occurred in areas which the model predicted as unusable habitat (i.e., errors of omission). Sites where errors of omission occurred contained water depths and velocities that were similar to areas predicted to have spawning, but had higher ($\sim 6\%$) lateral slopes.

Table 2.3. Final logistic regression model for predicting the probability that a habitat cell would be suitable spawning habitat for fall chinook salmon (*Oncorhynchus tshawytscha*) in the Hanford Reach (log-likelihood = -67.2, $df = 4$). The intervals for calculating the odds ratios for velocity, depth, lateral slope, and the interaction term (velocity x depth) were 0.1, 0.5, 0.01, and 0.1, respectively. G (likelihood ratio test) is twice the difference in negative log likelihood between a model with and without the variable at $p < 0.05$. An asterisk indicates the variable contributes significantly to the model.

Variable	Regression coefficient (SE)	Odds ratio (95% C.I.)	G
Velocity (m/s)	13.7 (2.3)	3.9 (2.5-6.2)	118.3*
Depth (m)	0.3 (1.1)	1.2 (0.4-3.4)	0.07
Lateral slope (m/m)	-23.2 (8.5)	0.8 (0.7-0.9)	8.9*
Velocity x depth	-1.7 (0.7)	0.8 (0.7-1.0)	9.9*
Constant	-12.6 (3.1)		

At Wooded Island, the model correctly predicted habitat cell designation 96% of the time with approximately 4% of the habitat cells predicted to be suitable spawning habitat (Table 2.4). The actual number of habitat cells that were suitable for spawning at Wooded Island was zero; thus, none of the sites predicted to have redds had redds. The predicted spawning sites at Wooded Island contained similar physical features found within spawning areas at Locke Island, i.e., mean lateral slope 1.5%, depth 2.9 m, and velocity 1.8 m/s.

Table 2.4. Contingency table/accuracy assessment of logistic regression model when used at Locke Island and Wooded Island in 1995. Habitat cells were predicted by the model to be either suitable spawning habitat (i.e., inside a redd cluster) or unsuitable spawning habitat (outside a redd cluster).

Locke Island		Actual designation – number (proportion)		
		Suitable	Unsuitable	
Predicted designation – number (proportion)	Suitable	69 (0.17)	39 (0.10)	108 (0.27)
	Unsuitable	17 (0.04)	279 (0.69)	296 (0.73)
		86 (0.21)	318 (0.79)	404 (1.0)
Wooded Island		Actual designation – number (proportion)		
		Suitable	Unsuitable	
Predicted designation – number (proportion)	Suitable	0 (0.0)	20 (0.04)	20 (0.04)
	Unsuitable	0 (0.0)	467 (0.96)	467 (0.96)
		0 (0.0)	487 (1.0)	487 (1.0)

DISCUSSION

Spatial pattern analysis confirmed that fall chinook salmon redds in the Hanford Reach occurred in clusters that averaged 800 m in length and approximately 120 m in width. The locations of these clusters were similar between 1994 and 1995. Redds were clustered when inter-redd distance exceeded 7 m, and within the clusters, the vast majority of redds were within 35 m of another redd. Additionally, there was strong evidence of a uniform distribution of redds within the clusters for short distances of 2 to 5 m. The crossover distance where patterns switched from uniform to clustered was approximately the distance between the centers of two adjacent redds. In other words, groups of fall chinook salmon redds were found in the same places and occurred in clusters, but within the clusters adjacent redds did not overlap and tended to be uniformly spaced.

Uniformity in the spatial patterns of fall chinook salmon redds within redd clusters at Locke Island likely resulted from interactions between individuals competing for space (Ludwig and Reynolds 1988). Interactions between neighboring chinook salmon females influenced redd site selection within a cluster of redds in the Nechako River, British Columbia (Neilson and Banford 1983). Although we were not able to directly observe spawner behavior, that the clusters were so tightly packed with redds suggests that the available space was exhaustively partitioned among redds. Competition for spawning locations within clusters of redds apparently occurred in the Locke Island study site despite the fact that escapements of fall chinook salmon to the Hanford Reach in 1994 and 1995 were 55 and 36% of peak escapement in 1987 (Dauble and Watson 1997).

If sites suitable for spawning were patchily distributed, as the non-random distribution of redds suggested, they must have a unique set of attributes that were not found throughout the entire study area. An alternative interpretation might be that spawning salmon do not have strong habitat-specific fidelity but chose to spawn

adjacent to sites chosen by the earliest arriving individuals in a season (Duker 1981). However, the high rates of reoccupation of redd clusters between years supports the site-specific fidelity interpretation. Specific habitat utilization and clustering of salmon spawning has been observed in other populations. For example, chinook salmon in the Kamchatka River, Russia, spawned in distinct patches even though similar habitat was available nearby (Vronskiy 1972). Chapman (1943) noted concentrated chinook salmon spawning in the mainstem Columbia River below Kettle Falls, Washington, where “the greater part of the river was not in use.” Clusters of chinook salmon spawning in the Nechako River corresponded to river bottom topography, with fish preferentially spawning along the lateral gravel ridges (Neilson and Banford 1983).

Areas of streambed predicted to be suitable habitat by the logistic regression model did not always include redds. Approximately one-third of the sites at Locke Island and all the sites at Wooded Island predicted to have redds using the physical attributes did not have redds (i.e., errors of commission). Some of this error can be explained by the fact that the number of redds in 1995 was 55% less than the number of redds in 1994. The logistic regression model was constructed using redd data from 1994 so not all the sites predicted to be suitable in 1995 would be filled. However, even in 1994 at Locke Island when redd densities were near capacity (D.R. Geist, unpublished data), errors of commission resulted. Most of the errors occurred adjacent to large clusters of redds. This suggested that the depth, lateral slope, and velocity in these locations was similar to the clusters, but the habitat apparently differed from the clusters in some other key attribute, which resulted in fewer fish colonizing these areas. In contrast, some areas of streambed predicted to be unsuitable by our model did receive redds (i.e., errors of omission). Errors of omission may result from spawners being forced into “sub-optimal” habitat located on the fringes of the clusters (Neilson and Banford 1983). Most of these errors occurred near the boundaries of the clusters where the lateral slope increased as a result of a change in riverbed form.

In either case, there were some unmeasured factor(s) that influenced redd site selection. For example, the long, sinuous, and narrow gaps frequently observed in the

redd clusters in the Hanford Reach (Figure 2.2) suggests that spawning is controlled by geomorphic features of the river bottom (i.e., sedimentary structures). The shapes of redd clusters were very similar to those commonly observed in longitudinal bars and channels deposited by gravelly braided rivers (e.g., Rust and Koster 1984). Hydraulic processes that form the longitudinal bars and channels in the river directly influence the topography (depth and slope) and the sediment size exposed on the river bottom. Geist and Dauble (1998) proposed that geomorphic features promote groundwater/surface water interactions within hyporheic habitats, and may play a role in spawning site selection by fall chinook salmon. In fact, upwelling from hyporheic habitats into the river in Locke Island spawning areas was greater than upwelling into non-spawning areas at Locke Island and Wooded Island (Geist, chapter 3 of this thesis). Further, the upwelling in spawning areas contained more oxygen and was composed of a higher proportion of river water than upwelling in non-spawning areas. These upwelling characteristics could provide cues that adult fall chinook salmon used to locate preferred spawning habitat.

Spawning habitat models, like PHABSIM, estimate spawning habitat using spawning habitat suitability criteria that are based on published or measured redd selection criteria (Bovee 1995). The use of river-specific suitability criteria is currently believed to be the best method for predicting spawning habitat for salmonids within rivers and streams (Shirvell 1989; Bovee 1995). However, our results suggest that spawning-area-specific suitability criteria may result in better predictions of available spawning habitat. Our logistic regression model used characteristics of spawning habitat measured within a local spawning area and represented the suitability criteria over a finer spatial scale than river-specific criteria. Consequently, it removed much of the variation between spawning areas that are widely separated and resulted in a narrower range of suitable spawning habitat and better predictions of spawning habitat than was previously achieved with river-specific criteria. That the logistic model, based on spawning habitat characteristics measured at Locke Island, correctly predicted low spawning utilization at Wooded Island showed that salmon responded to habitat in a

similar manner at each site. Additional evaluations of the model at other high-use spawning areas are needed, and may show that each individual spawning area contains a unique combination of physical habitat.

Fisheries managers use hydraulic models like PHABSIM because they expect the overestimation will result in over-protection of fish habitat. However, using broad habitat suitability criteria does not help define what physical features at any one site are controlling the formation of spawning clusters. This lack of understanding in what defines suitable spawning habitat results in the formulation of recovery goals for anadromous salmonids that are not supported by empirical data. It also directs limited resources to restoration efforts that are subject to failure. Our approach provides an alternative means for describing specific physical features that influence salmon spawning and improves our understanding of factors affecting redd site selection. This will ultimately lead to realistic recovery goals and efficient use of recovery resources.

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Chapter 3. Hyporheic Discharge of River Water into Fall Chinook Salmon Spawning
Areas in the Hanford Reach

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ABSTRACT

Fall chinook salmon (*Oncorhynchus tshawytscha*) spawned predominantly in areas of the Hanford Reach where hyporheic water discharged into the river channel. This upwelling water had a dissolved solids content (i.e., specific conductance) indicative of river water and was presumed to have entered highly permeable riverbed substrate at locations upstream of the spawning areas. Hyporheic discharge zones composed of phreatic groundwater or areas with little or no upwelling were not used by spawning salmon. Rates of upwelling into spawning areas averaged 1,200 L/m² per day as compared to approximately 500 L/m² per day in non-spawning areas. Dissolved oxygen content of the hyporheic discharge near salmon spawning areas was about 9 mg/L whereas in non-spawning areas dissolved oxygen values were 7 mg/L or lower. Physical and chemical gradients between the hyporheic zone and the river may have provided cues for adult salmon to locate suitable spawning areas. This information will help fisheries managers describe the suitability of fall chinook salmon spawning habitat in the mainstem of large rivers.

INTRODUCTION

There is evidence that intragravel flows influence redd site selection of fall chinook salmon (*Oncorhynchus tshawytscha*) (Geist and Dauble 1998). However, no quantitative studies have been conducted on the association of intragravel flows and redd site selection of fall chinook salmon in the mainstem of large rivers. Seepage outlets were suspected to be the reason for the concentrated chinook salmon spawning observed in the mainstem Columbia River near Kettle Falls, Washington (Chapman 1943). Elsewhere, chinook salmon spawned predominantly near gravel mounds that were suspected of increasing intragravel flow, but no measurements were made of water upwelling into the river channel (Burger et al. 1985). These observations are consistent

with those of other salmonids that use groundwater discharge to locate spawning sites, including brook trout (*Salvelinus fontinalis*) (Webster and Eiriksdottir 1976; Witzel and MacCrimmon 1983); sockeye salmon (*O. nerka*) (Lorenz and Eiler 1989); bull trout (*S. confluentus*) (Baxter 1997). Provided temperature and oxygen are not limiting, groundwater appears to have a positive influence on egg survival by moderating temperature, chemistry, and hydrology within the redd (Witzel and MacCrimmon 1983; Sowden and Power 1985; Curry et al. 1995).

In floodplain reaches of most large, alluvial rivers, upwelling flows are a combination of phreatic groundwater and river water that mix within hyporheic habitats below and lateral to the river channel (Stanford et al. 1996; Geist and Dauble 1998). Phreatic groundwater originates beneath land areas and contains a significant component of dissolved solutes derived from a long residence time in the subsurface (Freeze and Cherry 1979). In contrast, river water usually contains lower dissolved solutes and downwells into the riverbed at locations created where changes in riverbed topography relative to water depth creates zones of high hydraulic pressure. This water mixes with phreatic groundwater, and the mixed-water eventually upwells back to the river where the pressure head of the hyporheic water equals that of the channel bed (Vaux 1962, 1968; White 1993). Thus, the chemical composition and interchange between groundwater and surface water is a function of river bed topography, sediment permeability, depth of alluvium, and river discharge (Vaux 1962; Vervier et al. 1992; Harvey and Bencala 1993; Brunke and Gonser 1997). In this paper, hyporheic discharge includes a mix of phreatic groundwater and river water that discharge from the hyporheic zone into the river channel.

Fall chinook salmon redds are often clustered, providing evidence that spawning areas contain specific habitat characteristics that are not widely available (Geist and Dauble 1998; Geist et al., chapter 2 of this thesis). Lateral slope of the river bottom and mean water column velocity were significantly different inside and outside fall chinook salmon redd clusters in the Hanford Reach of the Columbia River (Geist et al., chapter 2 of this thesis). However, almost 50% of the areas predicted to have redds did not, and

the authors suggested hyporheic discharge may influence redd site selection. Understanding the interaction of groundwater and surface water within hyporheic habitats will allow fisheries managers to better define fall chinook salmon spawning habitat requirements. A better understanding of these requirements is needed because restoration efforts that are presently being planned include alteration of mainstem habitats through dam removal and reservoir drawdown, and reintroduction of fall chinook salmon into mainstem habitats that have been blocked by hydroelectric development (NPPC 1994; ISG 1996).

The purpose of this study was to evaluate the relationship between hyporheic discharge and fall chinook salmon spawning site selection in the Hanford Reach of the Columbia River. Hyporheic discharge was assumed to affect spawning site selection by providing cues (chemical, temperature, and physical) for pre-spawning adults to locate spawning reaches (usually 2 to 5 km in length). Once these reaches were “discovered”, hyporheic discharge was assumed to correlate with the distribution of redd clusters (500 to 800 m in length, 120 m in width; Geist et al., chapter 2 of this thesis) within these river reaches. I hypothesized that the physical and chemical characteristics of the hyporheic discharge in areas where fall chinook salmon spawned (both at the reach and cluster scale) would be different than the discharge in non-spawning areas. This hypothesis was tested over a range of river conditions and spawning seasons (1995 through 1997) between and within two sites previously studied for fall chinook salmon spawning habitat suitability (Geist et al., chapter 2 of this thesis). My evaluation showed that hyporheic discharge into the Hanford Reach was an important aspect of fall chinook salmon spawning site use. This information will be useful in describing the suitability of fall chinook salmon spawning habitat in other large rivers.

STUDY AREA

The Hanford Reach is the last unimpounded section of the mainstem Columbia River in the United States (Figure 3.1). Flow in the Reach is regulated by water storage

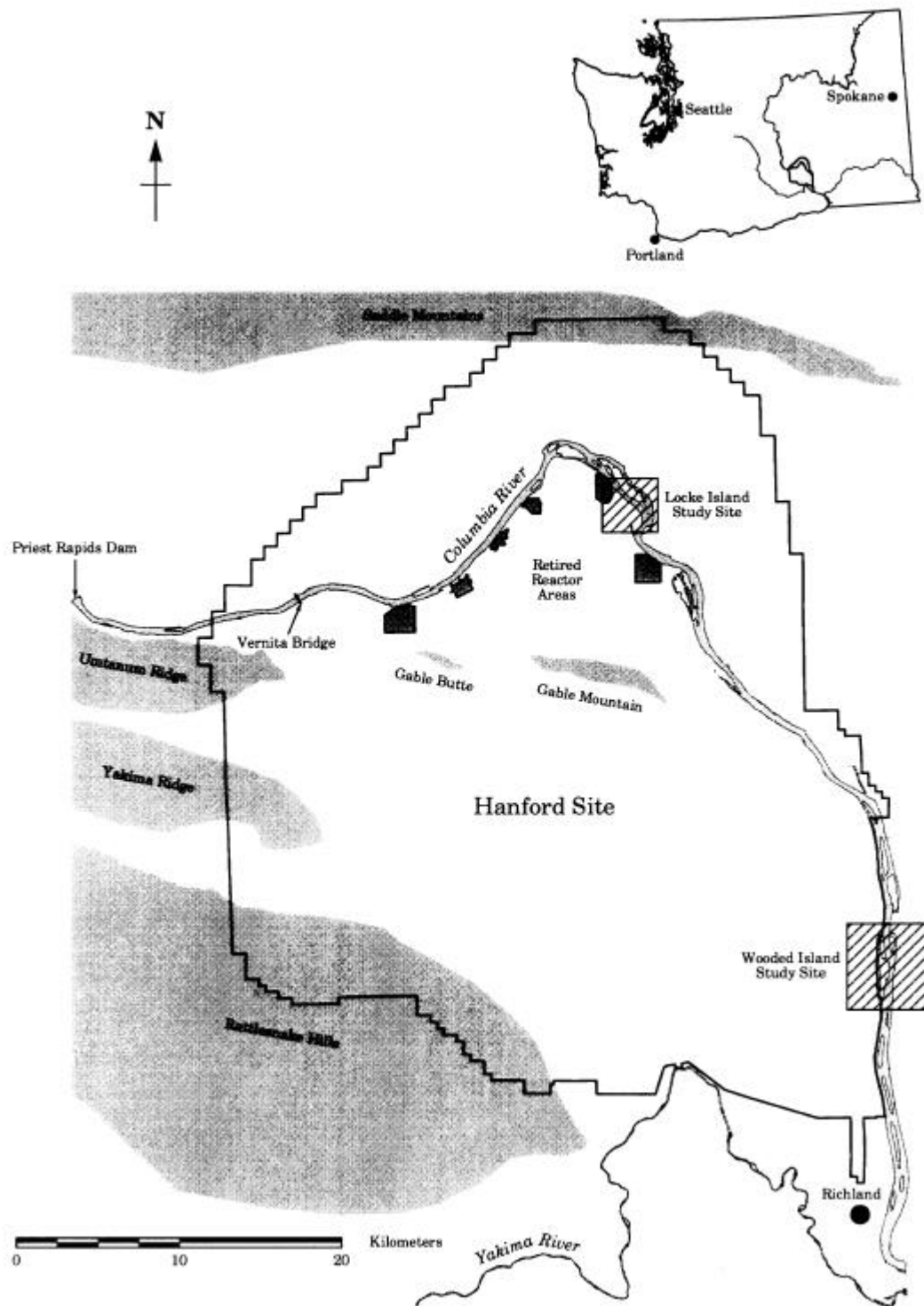


Figure 3.1. The Hanford Reach of the Columbia River showing the two study sites.

practices at upstream hydropower dams, including Grand Coulee and Priest Rapids dams. The mean daily discharge of the river varies seasonally from about 1,140 to 7,070 m³/s and because of rapid water releases in response to power demand at Priest Rapids Dam, water levels in the Reach commonly fluctuate 2 to 3 m per day. The daily average discharge through the Hanford Reach during peak fall chinook salmon spawning ranged from about 1,200 to 3,800 m³/s, 1959 – 1985 (Dauble and Watson 1997).

The association between fall chinook salmon spawning and hyporheic discharge was examined at Locke Island (Rkm 595-608) and Wooded Island (Rkm 560-563; Figure 3.1). The Locke Island study site has much higher fall chinook salmon redd densities than the Wooded Island site. For example, the average annual fall chinook salmon redd count at Locke Island from 1990 to 1995 was 513 (range 340 to 855) while the average redd count at Wooded Island during the same time period was 10 (range 0 to 32) (D. Dauble, Pacific Northwest National Laboratory [PNNL], unpublished data). Details about these study sites and site-specific fall chinook salmon spawning habitat use were previously described by Geist et al. (chapter 2 of this thesis).

METHODS

During the fall chinook salmon spawning seasons (October and November; Dauble and Watson 1997) from 1995 to 1997, mini-piezometers and internal-drive-rod piezometers were installed within the study sites. Mini-piezometers were installed following the methods described in Lee and Cherry (1978). Each mini-piezometer consisted of a 10 cm piece of polyethylene tube (9.5 mm o.d., 6.4 mm i.d.) that was attached on one end to an expendable drive point and on the other end to a length of polyethylene tubing (6.4 mm o.d., 4.8 mm i.d.). There were approximately twelve 3.2-mm-diameter perforations in each 10-cm section of tube. The perforated section of the tube was wrapped three times with 240 µm nitex screen and secured with adhesive.

Internal drive-rod piezometers were installed following the methods described in Geist et al. (1998). Each internal-drive-rod piezometer was constructed of a 184- or 215-cm section of steel-pipe (4.2 cm o.d., 3.5 cm i.d.) with a solid steel drive point welded to one end and a variable-length extension attached to the other end. A 30-cm section of the piezometer was perforated with 3.2-mm-diameter holes which were sometimes screened using a 2.5-cm-diameter line strainer screen.

Piezometers were installed within the river channel in groups of three or four with each piezometer installed to a different depth below the riverbed. The distance between piezometers usually did not exceed 30 cm. The average installation depth (i.e., below the riverbed) of piezometers in 1995, 1996, and 1997 was 97, 71, and 99 cm, respectively. The water depth of the river where piezometers were installed was usually ≤ 1 m but three piezometers were installed at Locke Island in water that was 3 to 4 m deep. Piezometers were placed in salmon spawning areas at Locke Island, and in areas not used for spawning at both study sites. Although a few salmon spawn at Wooded Island each year, there are no areas of extensive spawning. Spawning areas were defined as clusters of at least 25 redds with individual redds no greater than 50 m apart. Redd locations were based on aerial photographs taken following the peak of fall chinook salmon spawning within both study sites in 1994 and 1995. Details on redd cluster definition and redd mapping are found in Geist et al. (chapter 2 of this thesis). In all cases piezometers associated with spawning areas were within 75 m of the redd cluster, and usually within 50 m. In contrast, piezometers associated with non-spawning areas were almost always greater than 100 m from redd clusters. The resulting number of piezometers installed is shown in Table 3.1.

Once in place and operational, the piezometers were used to sample specific conductance ($\mu\text{S}/\text{cm}$ at 25°C), water temperature (T , $^\circ\text{C}$), dissolved oxygen (DO , mg/L), and hydraulic head (h , cm) of the hyporheic water. These parameters were also measured on a contiguous river sample. Specific conductance was the primary measure

Table 3.1. The number of individual piezometers (piezometer groups) installed at Locke Island and Wooded during the fall chinook salmon (*Oncorhynchus tshawytscha*) spawning seasons from 1995 through 1997. The definition of spawning areas is provided in the text.

Year	Wooded Island	Locke Island	
		Spawning areas	Non-spawning areas
1995	12 (4)	8 (3)	9 (5)
1996	9 (4)	12 (5)	11 (3)
1997	9 (3)	14 (3)	5 (2)

used to differentiate phreatic groundwater from surface water; specific conductance of undiluted groundwater adjacent to the Hanford Reach averages 300-400 $\mu\text{S}/\text{cm}$ while the river water averages ~ 150 $\mu\text{S}/\text{cm}$ (Peterson and Johnson 1992; Dresel et al. 1995). The differences in temperature (ΔT) and hydraulic head (Δh) were based on the piezometer reading (hyporheic water) minus the reading from its paired river sample. Individual piezometers were sampled an average of 7, 4, and 2 times during the spawning seasons in 1995, 1996, and 1997, respectively. Measurements of water temperature and specific conductance were either made on a water sample that was extracted from the piezometer using a low-volume peristaltic pump (the volume pumped for analysis was at least equal to the storage volume of the piezometer) or sampled in-situ within the piezometer after pumping. DO was measured in a sample that was continuously pumped from the piezometer; placing the DO probe directly in the piezometer to obtain DO measurements did not prove satisfactory. Permeability of sediments was large relative to pumping rate so that the measured water was not aerated. All river measurements were made in-situ immediately adjacent to the piezometer. Measurements of specific conductance and temperature were made with a temperature/conductivity meter (YSI model 30) and DO was sampled with a DO meter (YSI model 95) and/or with the use of a portable HACH kit (model DR2000).

Hydraulic head measurements were taken from the top of the piezometer using an electrical interface measuring tape (Solinst). The hydraulic head measurements were used to calculate the vertical hydraulic gradient (VHG) for each piezometer:

$$VHG = \frac{\Delta h}{L}$$

where Δh was the hydraulic head inside the piezometer minus the hydraulic head of the river (cm), and L was the distance below the river bed to the top of the piezometer perforations (cm). The VHG is a unit-less index with positive values indicative of an energy gradient sufficient to produce upwelling (i.e., hyporheic discharge zones) and negative values indicative of a gradient sufficient to produce down-welling (i.e., hyporheic recharge zones) (Freeze and Cherry 1979; Dahm and Valett 1996).

Hydraulic conductivity of the riverbed sediments was measured at each study site in 1997 using a modified slug test (Freeze and Cherry 1979; Dahm and Valett 1996). Slug tests were performed inside of internal drive-rod piezometers (Geist et al. 1998) that were installed to depths ranging from 40 to 152 cm below the river bed. Each test consisted of inserting a slug rod (2.5 cm o.d.) into the piezometer and allowing the hydraulic head to stabilize; measuring the initial hydraulic head within the piezometer; and then rapidly withdrawing the slug rod and recording the time for the head to recover. Hydraulic head was measured during the test every 0.25 seconds with a pressure transducer (KPSI Model 30S-112-0010) and data logger (Campbell Scientific CR10). Two replications were conducted at each piezometer; ten piezometers were measured at Locke Island and six at Wooded Island. Hydraulic conductivity (K) was calculated with the following formula (Hvorslev 1951):

$$K = \frac{r^2 \ln(L / R)}{2LT_0}$$

where K is the hydraulic conductivity (cm/s); r , radius of piezometer (1.75 cm); R , radius of piezometer screen (1.27 cm); L , length of piezometer screen (30 cm); and T_0 , time for hydraulic head in the piezometer to recover to 37% of initial change after the

slug rod was removed. An estimate of the specific discharge (v ; cm/s) into the Columbia River was made using the Darcy relationship (Freeze and Cherry 1979):

$$n = K \times VHG$$

where K and VHG were as previously defined.

The effect of diurnal fluctuations of river stage (i.e., discharge) on hyporheic discharge was monitored in five piezometer groups that were representative of the study site conditions. A paired set of piezometer groups was monitored at non-spawning areas at Wooded and Locke Island. A second comparison was done between three piezometer groups installed across the channel within spawning and non-spawning areas at the Locke Island site. Absolute pressure (i.e., hydrostatic plus barometric pressure) of hyporheic and surface waters was recorded simultaneously every 15 minutes using self-contained data loggers (Levellogger, model 3001, Solinst) that were placed within internal drive-rod piezometers and river standpipes. Barometric pressure was recorded simultaneously using a pressure transducer (Vaisala Model # PTB101B) connected to a data logger (Campbell Scientific CR10) located along the bank of the river. Hydraulic head of the hyporheic and surface water was determined by subtracting the barometric pressure from the absolute pressure readings. The VHG was calculated from these readings.

Differences in physiochemical data of the hyporheic and surface waters between the Locke Island and Wooded Island sites were tested statistically with analysis of variance (ANOVA) and regression ($\alpha = 0.05$). With the exception of the hydraulic conductivity and DO data that were collected in 1997, the between-site comparisons were performed on data collected in 1995. The paired piezometer groups where continuous data loggers were installed was used to compare the effect of fluctuating river discharge on the vertical potential between hyporheic and surface waters. The effects of piezometer depth and river stage (water surface elevation of river) on physiochemical

parameters were evaluated at each site using regression analysis. Water surface elevations were acquired from continuous river stage recorders located throughout the Hanford Reach and operated by Bechtel Hanford, Inc.

Comparisons of the physiochemical data collected in fall chinook salmon spawning and non-spawning areas within the Locke Island site were also compared using ANOVA and regression analysis. The within-site comparison was conducted on a 1,200 x 400 m area within the Locke Island site (Figure 3.2) that was previously evaluated for spawning habitat suitability (Geist et al., chapter 2 of this thesis). A logistic regression model that was based on lateral slope of the riverbed, water velocity, and water depth incorrectly predicted spawning to occur within this area. The physiochemical data used in the comparisons included specific conductance and temperature (1996 and 1997), DO (1997), and hydraulic head and VHG (1996). The data from the continuous water level recordings were used to evaluate differences in response of hyporheic waters to fluctuating river discharge in spawning and non-spawning areas (Figure 3.2). The effects of piezometer depth and river stage on physiochemical parameters of spawning and non-spawning areas were also evaluated using regression analysis.

RESULTS

From 1995 through 1997 the daily average discharge of the river at Priest Rapids Dam during the fall chinook salmon spawning season (October and November) was similar and averaged 3,154 m³/sec (range 2,875 m³/sec in 1995 to 3,453 m³/sec in 1997). The distribution of salmon spawning at Wooded and Locke islands was consistent with previous years. In 1995, 1996, and 1997 there were 3, 5, and 28 fall chinook salmon redds counted at Wooded Island, and 340, 392, and 607 redds counted at Locke Island (D. Dauble, PNNL, unpublished data).

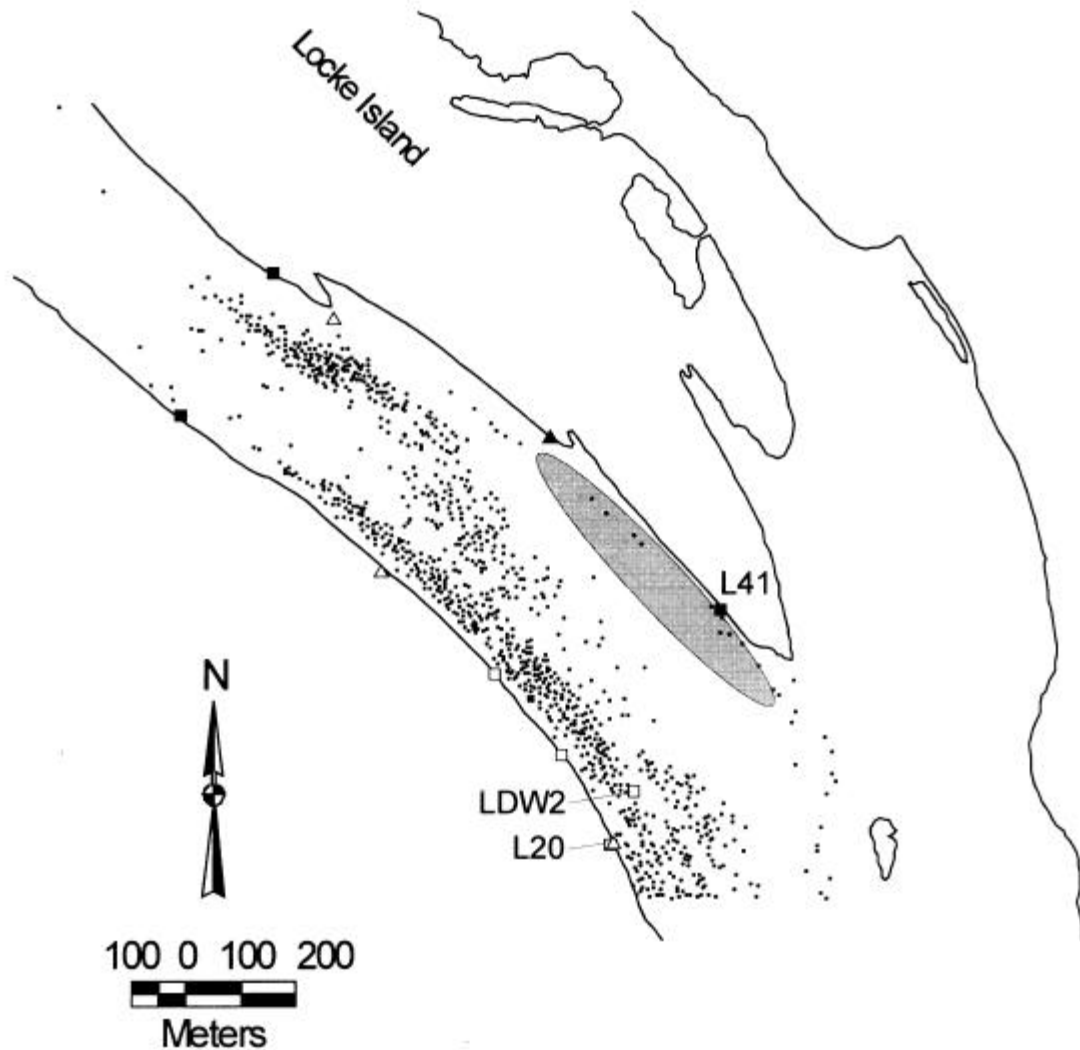


Figure 3.2. The Locke Island study site where comparisons of groundwater discharge were conducted between fall chinook salmon (*Oncorhynchus tshawytscha*) spawning and non-spawning areas. Groups of piezometers installed in 1996 (boxes) and 1997 (triangles) were used to collect this information. Open symbols show piezometer groups that were representative of spawning areas while closed symbols show piezometer groups representative of non-spawning areas (see text for definitions of spawning and non-spawning areas). Dots represent fall chinook salmon redds as digitized from aerial photographs taken in 1995. Shaded oval represents area of river bottom where a previous study (Geist et al., chapter 2 of this thesis) predicted spawning should occur but did not. Labeled piezometers (L20, LDW2, and L41) are highlighted to show individual piezometers where data loggers were installed in 1996 to monitor the change in vertical potentials under periods of fluctuating river discharge.

Between-Site Comparisons

The positive VHG and hydraulic head difference (Δh) between hyporheic and surface waters indicated that hyporheic water was predominantly upwelling into the river at the Locke Island and Wooded Island sites, but Δh and VHG values were significantly greater at Locke Island ($P = 0.002$ and $P = 0.0001$, respectively; Figure 3.3a,b). In addition, hyporheic discharge into the river at Wooded Island contained a significantly greater proportion of groundwater (i.e., higher specific conductance) than the upwelling into the river at Locke Island ($P = 0.005$; Figure 3.3c).

Specific discharge calculations gave an average flux out of the sediments on the order of 9.0×10^{-4} cm/s at Locke Island and 3.0×10^{-4} cm/s at Wooded Island. Thus, specific discharge of hyporheic waters was approximately 3 times larger at Locke Island than Wooded Island. However, there was no difference between sites in the temperature gradient between hyporheic and surface waters (ΔT ; $P = 0.41$; Figure 3.3d), or in the dissolved oxygen concentrations in the hyporheic waters (DO; $P = 0.21$; Figure 3.4). Hydraulic conductivity of the riverbed sediments also did not differ between sites ($P = 0.42$), averaging 0.02 (S.E. = 0.006) and 0.03 (SE = 0.008) cm/s at Locke Island and Wooded Island, respectively. The measured hydraulic conductivities were consistent with those of riverbed sediments composed of gravel and sand (Freeze and Cherry 1979).

River stage and physiochemical characteristics were weakly or not correlated (i.e., $r^2 \leq 0.10$) at both sites. This was also true when VHG was monitored over a range of river discharges that are typical in a 24-hour period during the spawning season (Figure 3.5). At Wooded Island, river stage changed approximately 1.2 m in a 16-hour period but VHG remained approximately constant within a group of piezometers (Figure 3.5a). A 0.7 m change in river stage at Locke Island over a 24-hour period also produced little change in VHG (Figure 3.5b).

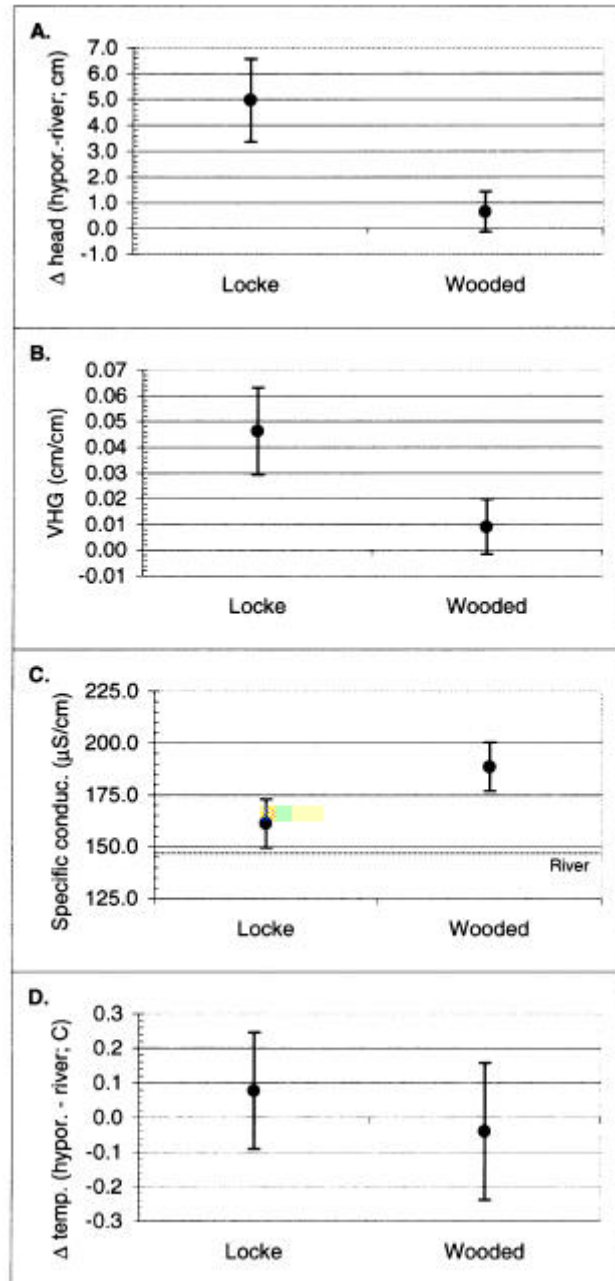


Figure 3.3. Physiochemical data collected from piezometers installed and monitored at the Locke Island and Wooded Island study sites during October and November 1995. Bars above and below the points represent the 95% confidence interval of the mean. (A) Hydraulic head of hyporheic water minus the hydraulic head of the river, (B) vertical hydraulic gradient (VHG) between hyporheic and surface waters where positive values indicated potential upwelling and negative values downwelling, (C) specific conductance of the upwelling areas and river, and (D) difference in temperatures between the hyporheic and surface waters.



Figure 3.4. Dissolved oxygen (DO) measurements of hyporheic water at Wooded Island; a non-spawning area at Locke Island; and a spawning area at Locke Island. DO concentrations of the river averaged between all three sites are also shown. Bars above and below the points represent the 95% confidence interval of the mean.

The physiochemical characteristics at both sites did not change with increasing distance below the river bed as indicated by the insignificant correlation between piezometer depth and all the measured parameters except specific conductance at the Locke Island site. However, the hydraulic conductivity tests showed that the time to recovery of hydraulic head within the hyporheic waters at Wooded Island increased significantly with increasing piezometer depth ($P = 0.02$, $r^2 = 0.78$; Figure 3.6). At Locke Island, recovery was independent of depth ($P = 0.42$, $r^2 = 0.08$). These results suggested that substrate permeability decreased with increasing depth at Wooded Island but not Locke Island.

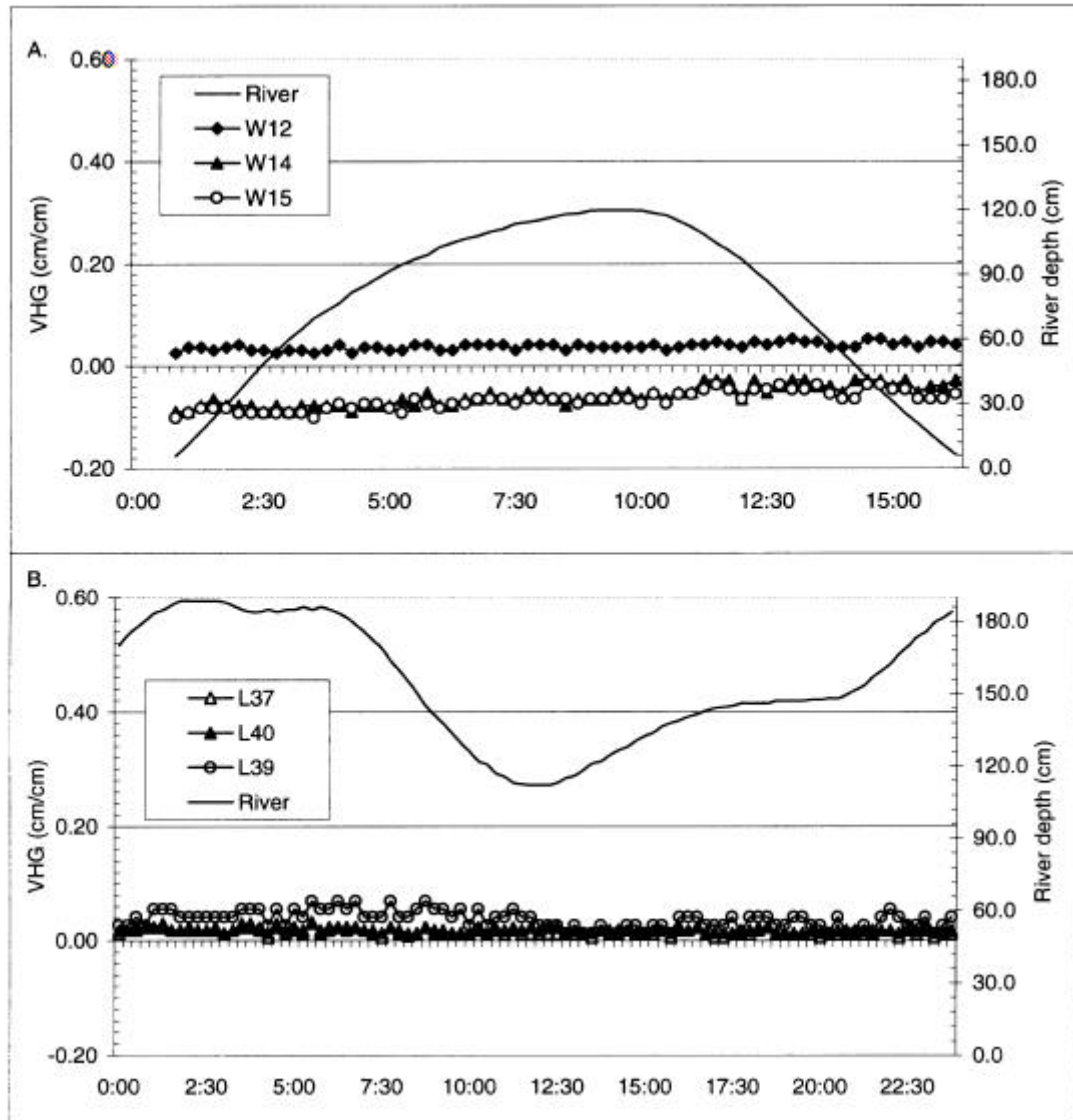


Figure 3.5. Continuous measurements of vertical hydraulic gradient (VHG) between hyporheic and surface waters at (A) Wooded Island (October 23, 1997) and (B) Locke Island (December 13, 1996). River depth represents the depth of the river within the standpipe attached to the piezometer group and is a surrogate for river discharge. The daily average discharge at Priest Rapids Dam was 3,256 and 2,966 m³/sec on October 23, 1997 and December 13, 1996, respectively.

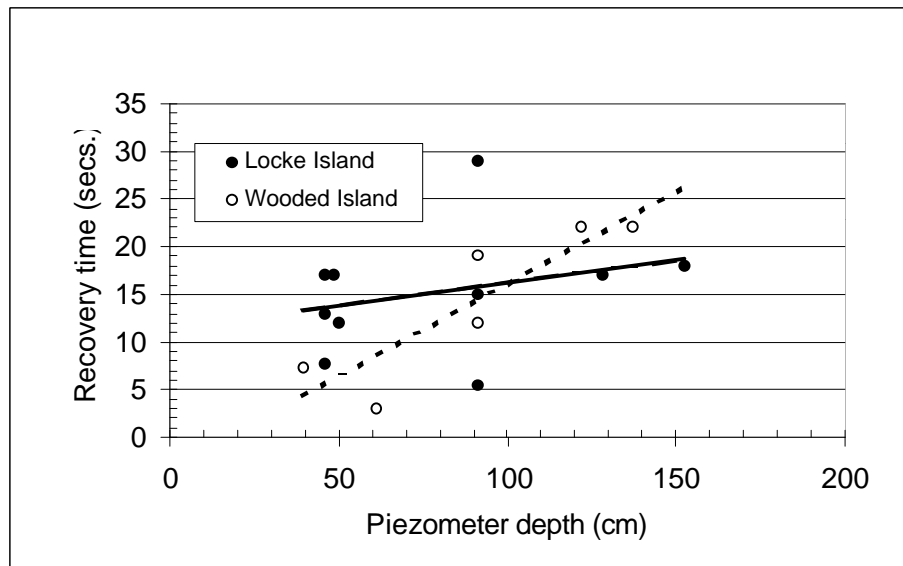


Figure 3.6. Recovery time to 37% of the initial hydraulic head following a slug-test within piezometers installed at Locke Island and Wooded Island. Solid circles and line represent the empirical data and trend line, respectively, for the Locke Island site. Open circles and dashed line represent the empirical data and trend line, respectively, for the Wooded Island site. The trend line at the Wooded Island site was significant ($P = 0.02$, $r^2 = 0.78$) but not significant at Locke Island ($P = 0.42$, $r^2 = 0.08$).

The continuous recordings of VHG also suggested substrate characteristics changed with increasing depth at Wooded Island but not at Locke Island. For example, one piezometer at Wooded Island located 91 cm below the river bed (W12) showed a very weak ($VHG = <0.05$) positive vertical gradient between the hyporheic and surface waters while two piezometers located 41 cm (W14) and 55 cm (W15) below the river bed showed a weak ($VHG <0.1$) but negative vertical gradient (Figure 3.5a). In contrast, there did not appear to be a difference in VHG for three piezometers installed 36 cm (L39), 84 cm (L37), and 100 cm (L40) below the riverbed at Locke Island (Figure 3.5b).

Within-Site Comparisons

Positive Δh and VHG values indicated that hyporheic water upwelled into the river in both spawning and non-spawning areas within the Locke Island study site (Figure 3.7a,b), but the Δh and VHG were significantly higher in spawning areas than non-spawning areas ($P = 0.0005$ and $P = 0.002$, respectively). Assuming a hydraulic conductivity of 0.02 cm/s in both spawning and non-spawning areas, there was an upward flux out of the sediments of approximately $1.4 \times 10^{-3} \text{ cm/s}$ ($1,200 \text{ L/m}^2/\text{d}$) in spawning areas and $6.0 \times 10^{-4} \text{ cm/s}$ ($518 \text{ L/m}^2/\text{d}$) in non-spawning areas.

Measurements of specific conductance showed that the hyporheic discharge in non-spawning areas contained significantly more phreatic groundwater than the discharge in spawning areas ($P < 0.0001$ 1996 and 1997; Figure 3.7c). The specific conductance of the hyporheic discharge increased $\sim 4 \mu\text{S/cm}$ ($r^2 = 0.72$; $P < 0.0001$) with every 10 m increase in distance away from redd clusters. Hyporheic discharge within spawning areas was more oxygenated than discharge in non-spawning areas ($P = 0.02$; Figure 3.4). There was no difference in the temperature gradient between hyporheic and surface waters in spawning and non-spawning areas in 1996 ($P = 0.44$) and 1997 ($P = 0.48$; Figure 3.7d).

River stage was not strongly related to the physiochemical characteristics of the hyporheic waters when measurements were taken at single points in time. In contrast, continuous measurement of hydraulic head in the hyporheic and surface waters showed a relationship between VHG and river stage in the spawning area but not in the non-spawning area (Figure 3.8). In the non-spawning area, VHG between the hyporheic waters approximately 1 meter below the river bed (L41) was not highly responsive to the fluctuating river discharge (Figure 3.8a). The response in the spawning areas was different depending on piezometer location and depth. In both areas the VHG was inversely related to river stage. However, in the near-shore piezometer (L20 on Figures 3.2 and 3.8b) the response of the hydraulic head of the hyporheic water 72 cm below the bed was almost instantaneous and actually switched from positive to negative

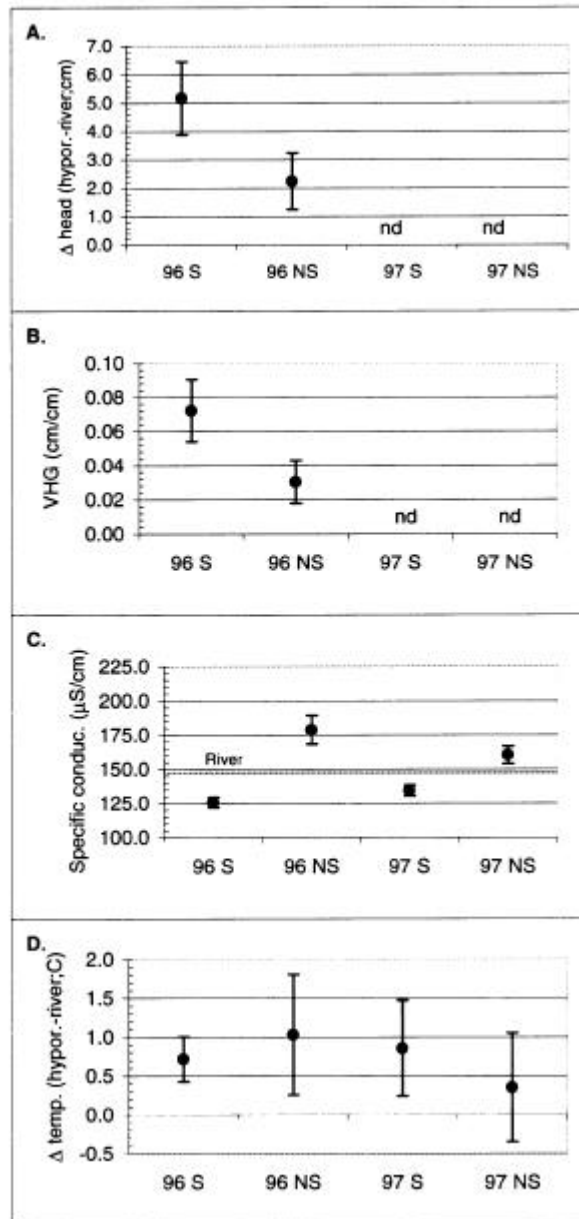


Figure 3.7. Physiochemical data collected from piezometers installed and monitored within the Locke Island site at spawning (S) and non-spawning (NS) sites during October and November, 1996 and 1997. Bars above and below the points represent the 95% confidence interval of the mean. (A) Hydraulic head of hyporheic water minus the hydraulic head of the river, (B) vertical hydraulic gradient (VHG) between hyporheic and surface waters where positive values indicated potential upwelling and negative values downwelling, (C) specific conductance of the upwelling areas and river (dashed line), and (D) difference in temperatures between the hyporheic and surface waters. nd = no data collected.

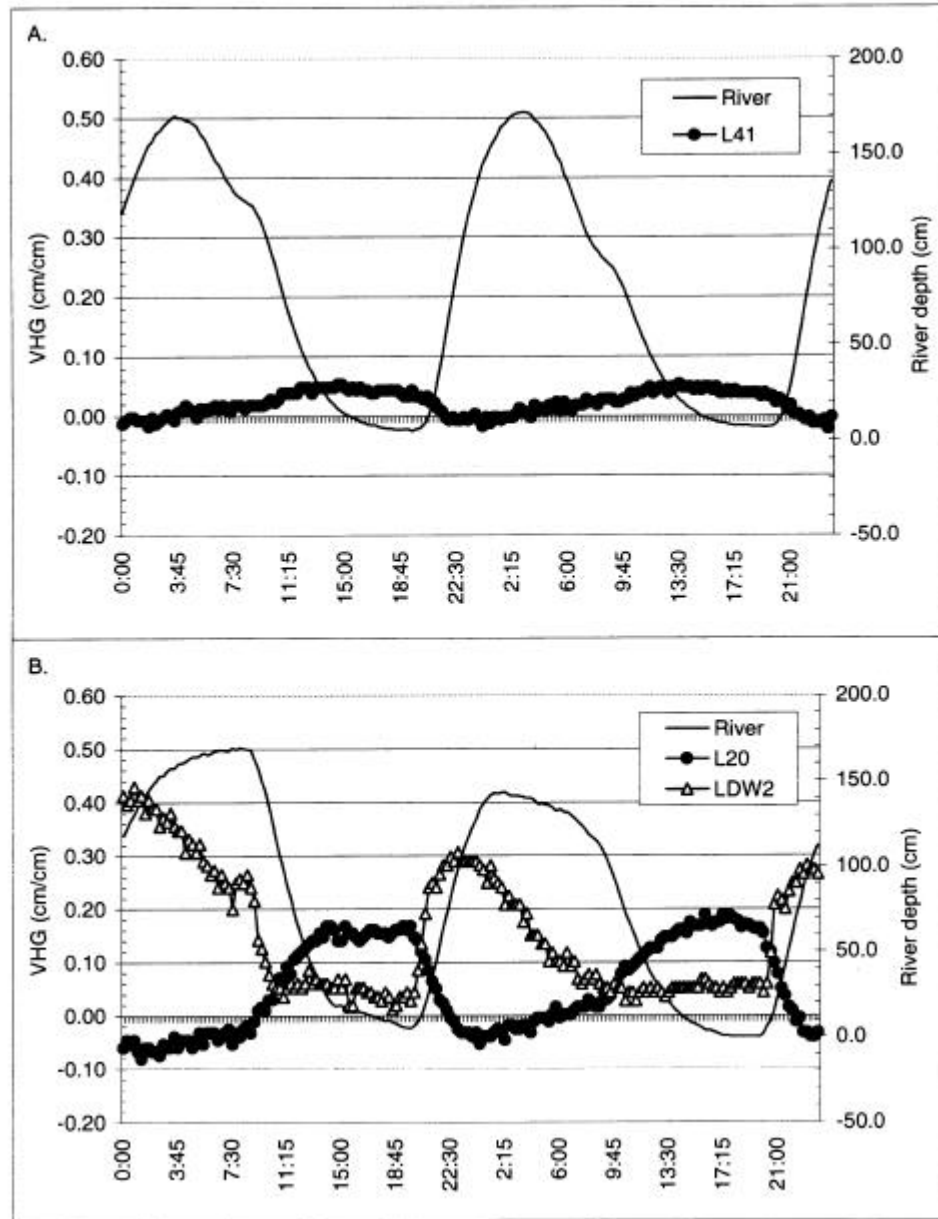


Figure 3.8. Continuous measurements of vertical hydraulic gradient (VHG) between hyporheic and surface waters at (A) Locke Island non-spawning site (November 13-14, 1996) and (B) Locke Island spawning site (November 20-21, 1996). River depth represents the depth of the river within the standpipe attached to the piezometer group and is a surrogate for river discharge. The daily average discharge at Priest Rapids Dam was 2,837 and 3,241 m³/sec on November 13-14, 1996 and November 20-21, 1996, respectively.

as the river level increased. In contrast, the VHG between the hyporheic and surface waters 61 cm below the bed and the river in the off-shore piezometer (LDW2 on Figures 3.2 and 3.8b) always remained positive and responded much more slowly than the near-shore piezometer (L2); the time delay between maximum river depth and minimum VHG was 10 to 15 hours while the delay between maximum VHG and minimum river depth was only 3 to 4 hours.

There were few significant correlations between piezometer depth and physiochemical characteristics within the Locke Island site and, where they were significant, the relationships were weak. The exception was in the non-spawning area in 1997 where specific conductance increased significantly with increasing distance below the river bed ($P = 0.04$; $r^2 = 0.91$). In contrast, there was no relationship within spawning areas during that same year.

DISCUSSION

Fall chinook salmon redd locations were highly correlated with hyporheic discharge that was composed of mostly river water and not phreatic groundwater. Hyporheic water moving into fall chinook salmon spawning areas had consistently higher specific discharge, higher dissolved oxygen, and lower specific conductance than discharge into non-spawning areas. Further, hyporheic discharge within areas predicted to be suitable spawning habitat (but not used) was similar to hyporheic discharge in areas not used by fall chinook salmon in the Hanford Reach (Geist et al., chapter 2 of this thesis).

That hyporheic discharge was dominated by river water suggests that sediment deposits are more permeable in the spawning areas than in the non-spawning areas. Geomorphic bed features (i.e., islands, gravel bars, riffles) of alluvial rivers are able to create hydraulic gradients sufficient to direct surface water into the bed (Stanford et al. 1996; Brunke and Gonser 1997). River water will be able to penetrate deeper into

hyporheic habitats if the riverbed is composed of alluvium that is highly permeable (Vaux 1962; White 1993). The deeper and more permeable the alluvium, the more that the physiochemical characteristics of the hyporheic waters will resemble surface water rather than groundwater. In contrast, the relative proportion of phreatic groundwater in hyporheic waters will be greater if the riverbed sediments are of low hydraulic permeability because river water will not be able to readily enter the substrate and dilute the groundwater (White 1993; Brunke and Gonser 1997).

Fall chinook salmon redds appear to follow longitudinal, hydraulically controlled bed features (Geist et al., chapter 2 of this thesis). It is possible that these spawning areas have more permeable alluvium that corresponds to depositional areas from previous flooding. Hydraulic conductivity tests showed that the permeability of the substrate decreased with increasing depth into the riverbed at Wooded Island (non-spawning site) but not Locke Island (spawning site). Field observations made at the Wooded Island study site suggested the presence of an impermeable layer approximately 60 cm below the bed at which point piezometers became noticeably more difficult to install. This was not the case at most locations at the Locke Island site. In addition, at Wooded Island there was a change in the vertical potential approximately 60 cm below the riverbed with groundwater recharge (i.e., downwelling) occurring above that point and groundwater discharge (i.e., upwelling) occurring below 60 cm.

Characteristics of hyporheic discharge helped explain aspects of fall chinook salmon redd patterns not explained by physical (hydraulic) features (Geist et al., chapter 2 of this thesis). For example, the dissolved oxygen of the hyporheic discharge in non-spawning areas at Locke Island was similar to the levels at Wooded Island which also had little or no spawning; these areas also had higher specific conductance of the hyporheic waters. In addition, in the non-spawning areas the proportion of phreatic groundwater in hyporheic water increased with increasing depth below the river bed, but stayed constant with depth in the spawning areas. These results suggest that less surface water mixes into the alluvium beneath the non-spawning areas as compared to spawning areas.

The hypothesis that hyporheic discharge in spawning areas was more influenced by the river than in non-spawning areas is supported by the diurnal fluctuations in VHG between hyporheic and surface waters. In non-spawning areas at both sites, the VHG did not respond to diurnal fluctuations in river discharge. However, in the spawning areas at Locke Island, fluctuating river stage was associated with rapid changes in VHG in near-shore piezometers, while the response was dampened in off-shore areas. This is consistent with other studies that show groundwater discharge is greatest near the shore-line interface and decreases exponentially with distance offshore (Winter 1974; Pfannkuch and Winter 1984).

It is apparent that hyporheic water of the Hanford Reach is composed of both river water and phreatic groundwater. The vertical and horizontal potentials of this water appear to be influenced by geomorphic bed features as well as fluctuating river discharge. The river gains water from the aquifer as it flows through the Hanford Reach. Diurnal fluctuations in river stage result in layering and mixing of groundwater and river water, dilution of groundwater constituents, and control mixing rates of groundwater and surface water (Hope and Peterson 1995). Fluctuations in Columbia River discharge affect groundwater elevations in wells located as far as 800 m from the river (Luttrell et al. 1992), but groundwater – surface water interactions occur primarily within a bank storage zone where river water is temporarily stored during periods of high river discharge, and then released back to the river as discharge recedes. River water and groundwater also interact within the continuously submerged portion of the river channel. The depth of the interface between groundwater and river water is variable, and dependent upon substrate permeability, longitudinal gradient of the riverbed, hydraulic gradient between the river and the aquifer, and the discharge of the river (Vaux 1962; Vervier et al. 1992; Hope and Peterson 1995). Within the upper portion of the river bed flow is suspected to occur mostly in a horizontal direction, while deeper the flow is more vertical and composed of higher and higher proportions of phreatic groundwater. In the Locke Island study area, river water has been found at depths greater than 9 m into the substrate (R. Peterson, CH2MHill, Richland, Washington,

personal communication). Thus, it appears that the permeability of the alluvium is greater in areas where fall chinook salmon spawn, and composed of a greater proportion of river water upwelling into the river channel.

The consistent occurrence of river water in hyporheic discharge into spawning areas suggests that upwelling of river water may have influenced homing of salmon to the spawning areas. Upwelling water produces temperature, physical (flowing water), and/or chemical (dissolved oxygen, dissolved ions) gradients in surface waters that could be used by salmon to search for a spawning area. For example, Curry and Noakes (1995) suggested that areas with both discharging and ion-rich water were used by brook trout to locate spawning areas in Canadian shield waters, but they found no difference in temperature gradients. Brook trout apparently used seepage velocity to select spawning sites in spring-fed ponds (Carline 1980). Chum salmon (*O. keta*) used temperature and discharge to locate spawning sites near groundwater discharge composed of both surface and phreatic groundwater (Leman 1993). Hansen (1975) determined that brown trout (*Salmo trutta*) used both temperature and dissolved oxygen to avoid areas of undiluted groundwater discharge. In a turbid river, sockeye salmon preferentially selected spawning areas near groundwater discharge, but surface water temperatures of spawning sites were no different than non-spawning sites (Lorenz and Eiler 1989). These studies suggest that salmonids respond to hyporheic upwelling, but the specific component of the upwelling that provides cues is species and location specific.

There was no evidence from the present study that temperature gradients between the hyporheic and surface waters provided cues for adult salmon to locate spawning areas. However, the water temperature of riverbed sediments during the fall chinook salmon egg incubation period (November through March; Becker 1985) was as much as 3°C warmer than the river (D.R. Geist, unpublished data). Warm groundwater discharge provides benefits to developing embryos by protecting the eggs from freezing, and optimizing incubation and emergence periods (Curry et al. 1995). Thus, there could be a selective advantage of spawning in groundwater discharge areas.

The ability of fish to detect gradients between hyporheic and surface waters will be a function of gradient intensity as determined by the rate of upwelling (Curry and Noakes 1995). The amount of upwelling in spawning areas at Locke Island was an order of magnitude higher than the amount of upwelling at the Wooded Island site and in non-spawning areas at the Locke Island site. Groundwater discharge into the Hanford Reach is only a small fraction ($<0.01\%$) of the total river discharge (Luttrell et al. 1992). Consequently, the ability of fall chinook salmon to detect a change in the physical characteristics of the upwelling would seem unlikely. However, estimates of groundwater discharge are dependent upon hydraulic conductivity of the riverbed sediments which can vary one to two orders of magnitude (Freeze and Cherry 1979). Thus, it is conceivable that groundwater discharge could two orders of magnitude higher or lower than this estimate of 0.01% .

Dissolved oxygen within sediments where fall chinook salmon spawned was significantly higher than DO in non-spawning areas. In both cases the level of DO was higher than the critical levels needed for the survival of eggs and alevins (~ 5 mg/L; Bjornn and Reiser 1991). Low DO was used by brown trout to avoid areas of groundwater upwelling, but concentrations ranged down to 2 mg/L in groundwater discharge zones (Hansen 1975). Dissolved oxygen ranged from 2.6 to 9.25 mg/L in steelhead (*O. mykiss*) redds and was positively correlated with survival of embryo although the effect of intragravel velocity could not be factored out (Coble 1961). In the present study, dissolved oxygen levels were likely a function of increased permeability of substrate within spawning areas, and secondarily important in site selection by pre-spawning fish.

It is well documented that salmon use olfactory cues to imprint upon the natural odors of their home stream during the pre-smolt to smolt life stage, and then use these odors to return to the stream as adults (Hasler and Wisby 1951; Hasler and Scholz 1983). For example, fingerling coho salmon (*O. kisutch*) that were imprinted to morpholine (a heterocyclic amine) at a concentration of 1×10^{-5} mg/L during the pre-smolt and smolt period returned 2 years later in significantly higher numbers to the

stream scented with morpholine (3×10^{-4} to 1×10^{-5} mg/L) than to a stream with a control chemical (Cooper et al. 1976). In another study, during their upstream migration 18 months after being imprinted to morpholine, adult coho salmon followed the shoreline of the river where morpholine was presented, but avoided the opposite shore (Johnsen and Hasler 1980). Based on electrophysiological experiments, the olfactory system of salmon can differentiate concentrations of some organic chemicals on the order of 1×10^{-11} M (Hara 1970). Apparently the ability to detect low concentrations of chemicals is possible because during sexual maturation, sex hormones (e.g., estradiol 17-B, testosterone) cause hypersensitivity of the olfactory system (Hasler and Scholz 1983). It is conceivable that chemical cues resulting from hyporheic discharge are detectable by fall chinook salmon that spawn in the Hanford Reach.

If olfactory cues are being used to guide fall chinook salmon back to spawning areas, chemical cues may be used as an attractant to the river water component of the discharge or as an avoidance of the groundwater component. Although it is not exactly known what specific compounds in home streams that salmon imprint on, organic compounds appear to play a role in attracting fish (Hasler and Wisby 1951). Inorganic compounds elicited an olfactory response (i.e., electrophysiologically), but organic odors were suspected to be better indicators of lake-water than inorganic ions in a study of sockeye salmon migration (Smith 1985). The total organic content of the groundwater discharge was not measured in this study. However, groundwater on the Hanford Site contains a higher proportion of nitrates, calcium bicarbonate, and chloride than river water (Hartman and Dresel 1998; Dirkes and Hanf 1998). Laboratory tests of the effects of these chemicals on migratory fish give inconsistent results: Atlantic salmon (*S. salar*) avoid chlorine (Smith 1985), while blacknose dace (*Rhinichthys atratulus*) are attracted to low levels of free chlorine (Fava and Tsai 1976). CaCl_2 , at concentrations found in natural lakes, was suspected to be an effective odorant for sockeye salmon fry (Bodznick 1978). Chemical differences between groundwater and surface water may provide cues that fall chinook salmon can use for olfactory discrimination. However, additional effort would be needed to quantify the concentration of inorganic

and organic compounds present within groundwater discharge areas before a conclusion could be drawn on the relative importance of chemical cues in redd site selection by fall chinook salmon in the Hanford Reach.

CONCLUSIONS

Hyporheic discharge, composed of mostly river water, was different between spawning and non-spawning areas of fall chinook salmon. Substrate within spawning areas was also more permeable than substrate within non-spawning areas. The physical and chemical gradients between hyporheic and surface waters were greater in spawning areas than in non-spawning areas, suggesting that these gradients, along with standard hydraulic features of river channels, may provide cues for adult salmon to locate suitable spawning areas.

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Chapter 4. A Method For Installing Piezometers in Large Cobble-Bed Rivers

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ABSTRACT

An impact-drive-point method is described for emplacing piezometers in a cobble river bottom where this has previously been difficult without the use of drill-rigs. To force the drive-point piezometers through cobble, the vibrational impact of an air-powered hammer was carried directly to the drive-point by the use of an internal drive-rod. After insertion to depth, the drive-rod was removed from the lower portion of piezometer and a standpipe was added to extend the piezometer above the river level. Piezometers installed in this way have permitted water quality analysis and dynamic measurement of vertical potentials in cobble sediments ranging in size from 2.5 to >30 cm and the method has been successfully used in the Columbia River, USA, and Töss River, Switzerland. This innovative method provides information on the hydrodynamics of pore-waters in highly permeable, cobble deposits that are common in high energy river and lake bottoms. Piezometers installed using the internal drive-rod method facilitate the assessment of the temporal and spatial dynamics of recharge and discharge at the groundwater/surface water interface and analyses of the ecological connectivity between the hyporheic zone and surface waters of rivers and streams. This information will lead to improved management decisions related to our nation's groundwater and surface water supplies.

INTRODUCTION

The study of the interaction between groundwater and surface water within the cobble bed material of large rivers is of great interest to hydrogeologists and ecologists. Measurements of hydraulic gradients and the physical-chemical characteristics of groundwater are necessary to understand contaminant transport between groundwater and surface water and the ecological significance of groundwater/surface water interactions within the subsurface zone of rivers and streams (termed *hyporheic zone*; see

reviews by White 1993, and Brunke and Gonser 1997). This information is needed to improve management of watersheds and our nation's groundwater and surface water (Job and Simons 1996). However, a major obstacle in providing more detailed information on groundwater/surface water interactions is that installation of monitoring and sampling devices in many rivers is still problematic (Dahm and Valett 1996).

Groundwater wells (e.g., a standpipe with a diameter >10 cm, screened over a large interval, and installed using a drill-rig) located throughout the floodplain were used to measure the large-scale movement of sub-surface flow and ecological connectivity within the Flathead River basin (Stanford and Gaufin 1974; Stanford and Ward 1988). Similar methods have been used in European rivers to study the invertebrates that inhabit the hyporheic zone (see Obrdlik et al. 1992). However, installation costs and/or access for drill-rigs often prohibits the use of monitoring wells. In addition to the problems of cost and access, wells that are installed using an auger have a disturbed annulus along the length of the standpipe (Desaulniers 1983). When piezometers are set by driving or vibrating, there is much less disturbance and there may be an adequate seal above and below the screen.

Installing piezometers into the bed material of rivers using drive-point techniques is not new (e.g., see Pollard 1955; Terhune 1958), and usually involves applying force on the top of the standpipe and pushing the entire pipe through the bed material. However, the drawback of this technique is that additional lengths of standpipe can not be added to the piezometer unless precautions are taken to prevent damage to the top of the piezometer. One modification to this technique includes the use of an outer casing that surrounds and protects an internal piezometer (Lee and Cherry 1978; Desaulniers 1983). In this modification the force is still applied to the top the casing which pushes the drive-point into the sediment, however, once the piezometer is at the desired depth, the casing is removed leaving the piezometer and drive-point in place; lengths of standpipe can then be added as needed. A disadvantage of this technique is that a disturbed annulus is created along the length of the piezometer when the casing is removed which may result in an improper seal between the piezometer and sub-surface material. This

presents a problem in groundwater/surface water interaction studies that are conducted in large cobble river bed material because water may “leak” along the length of the piezometer giving erroneous results.

We developed a technique that enabled the investigation of the sub-surface regions of large rivers in areas where study-site conditions were too difficult for the use of hand tools to install piezometers, and access for a drill-rig was difficult or cost-prohibitive. This method involves the use of an internal drive-rod that acts directly on the drive-point and “pulls” the piezometer into place. Because an outer casing is not used, the seal between the cobble-bed material and the piezometer standpipe may be no worse than the natural river bed in the absence of the standpipe. Piezometers installed in this way have permitted water quality analysis and dynamic measurement of vertical potentials in cobble sediments ranging in size from 2.5 to >30 cm. The method has been successfully used in the Columbia River, USA, and Töss River, Switzerland. We describe here the technique as it was used in the Hanford Reach of the Columbia River. Limited data are provided to demonstrate that the method is able to differentiate between groundwater and surface water within the highly permeable cobble bed-material of a large river.

METHODS

Each piezometer consisted of a 184- or 215-cm section of 4.2 cm diameter (i.e., 1¼ inch nominal, schedule-40) steel pipe with a solid steel drive-point welded to one end and a variable-length extension attached to the other end (Figure 4.1a). A 30-cm section of the piezometer near the drive-point was perforated with 3.2 mm diameter holes to allow entry of water and hyporheic organisms. Directly below the perforations was a 31-cm section of open pipe to allow for the accumulation of fines that entered the piezometer during installation or after the piezometer was in place. In other study areas where fine material is not present, the length of open pipe could be shortened which would result in increased penetration depth of the piezometers.

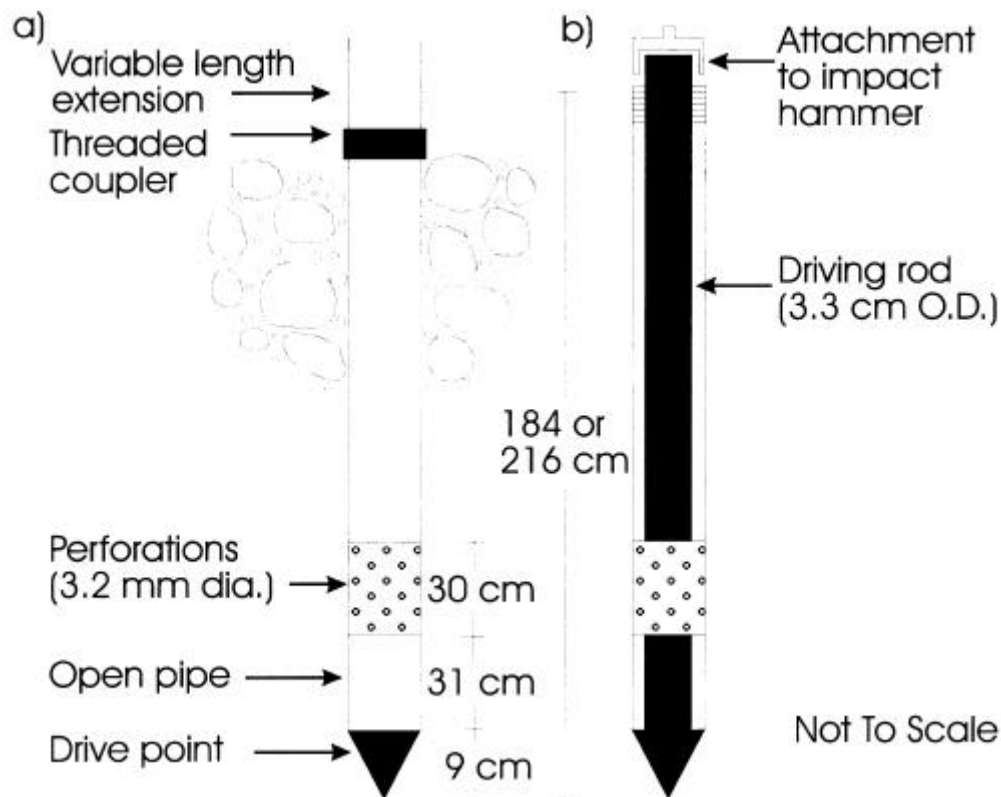


Figure 4.1. (a) Schematic showing the piezometer after installation into the river bed. The initial standpipe that was emplaced in the river bed was made from 4.2 cm o.d. (1¼ inch nominal), schedule-40 steel pipe with a solid steel drive-point welded to one end and threaded on the other end. Once the piezometer was in place, a variable length extension (same diameter) was attached to the standpipe using a threaded coupler. This extended the top of the piezometer above the river surface. A short section of open pipe near the bottom provided for the accumulation of sediments that entered the piezometer through the perforations during installation. These sediments were later removed using short bursts of air to lift them out of the piezometer. (b) The piezometer with solid steel drive-rod (1 inch nominal) and air-powered impact hammer attachment prior to installation. The solid steel drive-rod acts directly on top of the drive-point and “pulls” the piezometer into the sediment. Once the piezometer is installed to depth, the rod is removed using a set of pipe wrenches or, if necessary, a truck jack.

The piezometer was driven into the substrate using a hand-operated, 27-kg air-powered impact hammer attached via hose (12.7 mm dia.) to an air compressor. Two different air compressors were used depending on site accessibility. Where it was possible to drive a vehicle to an installation site, we used an air compressor and storage tank that were mounted on the back of a flatbed truck. The compressor and storage tank weighed approximately 180 kg and measured 122 cm long, 91 cm tall, and 36 cm wide. This set-up had a storage tank capacity of 120 L and delivered air to the hammer at a rate of 0.4 m³/min. We could not always drive a vehicle immediately adjacent to the installation site, and often had to extend up to 250 m of hose between the truck and the piezometer installation site. This did not significantly affect the performance of the impact hammer. In situations where we were not able to drive a vehicle to within 250 m of the installation site, we used a portable air compressor carried in the back of a 6 m jet-boat. The portable air compressor weighed approximately 82 kg, and measured 109 cm long, 66 cm tall, and 48 cm wide. It was capable of delivering air at 0.4 m³/min and had a storage tank capacity of approximately 30 L. The hose length in this situation did not usually exceed 10 m.

The impact hammer was applied to the top of a solid steel drive-rod (2.5 cm dia.) that was inserted inside the piezometer and directly contacted the top of the solid drive-point (Figure 4.1b). In order for the operator of the impact hammer to reach the top of the drive-rod at the beginning of each installation, he/she would either climb a ladder that was placed next to the piezometer or work from the front of the jet boat or back of the well truck. Two people were necessary to install the piezometers; one person operated the impact hammer while the second person supported the ladder or held the boat in position. A ladder was only used if the boat or truck could not be positioned adjacent to the piezometer and if the site conditions did not present a safety hazard (i.e., high river current, uneven river bed). Although we did not use scaffolding in the Hanford Reach, this would provide a more stable work surface than the ladder in situations where the boat or the truck could not be positioned close to the piezometer.

Pounding continued until the perforated section of the piezometer was at the desired depth. This usually resulted in the top of the 184- or 215-cm long steel pipe protruding above the substrate approximately 5 to 15 cm. The drive-rod was then removed by simultaneously rotating and lifting the bar with two pipe wrenches. Depending on the amount of fines that had accumulated in the bottom of the piezometer, a truck jack was sometimes necessary to remove the drive-rod. The height from the top of the standpipe to the river bed was recorded before and after drive-rod removal to ensure the perforated portion of the piezometer did not move upward as the drive-rod was removed. The tighter the drive-rod fit inside the piezometer, the less the drive-rod jammed due to sediment accumulation. After the drive-rod was removed, short bursts of air from the air compressor were used to “lift” out sediment that had accumulated in the bottom of the pipe. These short bursts reduced the likelihood of disturbing the outer seal between the bed material and the piezometer.

Piezometers were usually installed in clusters of four and arranged in a diamond configuration; one point of the diamond faced upstream. Each piezometer within the cluster was installed to a different depth, with the deepest piezometers usually placed at the upstream point of the diamond. The distance between individual piezometers within the cluster usually did not exceed 1 m. Additional lengths of pipe were threaded to the top of the 184- or 215-cm long pipe depending on the depth of the perforated section and river stage. For example, river stage in the Hanford Reach can fluctuate up to 0.2 m/h daily, and up to 3 m during a day or season depending on discharge. Therefore, to ensure the tops of the piezometers stayed above the river stage during periods of high discharge, we adjusted the height from the river bed to the top of the piezometers to at least 3 m (range 3.1 to 3.8 m). If the piezometer posed a threat to navigation, the additional lengths of standpipe were removed and the piezometer was capped between sampling periods.

We have noted that if the piezometers are not physically supported they can break off near the threads during increased river discharge and when debris accumulates around the piezometers. To partially alleviate this problem, each of the piezometers

within the cluster was attached to another piezometer using two-way swivel clamps and at least two (and sometimes up to four) support pipes (1½ inch nominal). Maximum support between adjacent piezometers was achieved by arranging the support pipes in a crisscross pattern, and ensuring the swivel clamps were attached to one of the piezometers at a point below the threaded portion of the piezometer pipe. By design, the diamond configuration deflects floating debris around the cluster and minimizes flow resistance. However, in the Töss River, Switzerland, clusters of piezometers supported in this manner have withstood the accumulation of large debris, and actually created log jams along the river's shoreline.

Once in place and developed, the piezometers were used to sample electrical conductivity and to compare the water surface elevation of the sub-surface water with contiguous river water. A 500-ml water sample was extracted from the piezometer and electrical conductivity was measured for this sample using a conductivity/temperature meter (YSI model 30). The volume pumped for analysis was at least equal to the storage volume of the piezometer. Water surface elevations were measured from the top of the piezometer using an electrical interface measuring tape (Solinist). The water surface elevation, local river level, and the depth of the piezometer perforations below the river bed were used to calculate the vertical hydraulic gradient (VHG) at each piezometer location:

$$\text{VHG} = \Delta h / \Delta L \quad (1)$$

where Δh was the water surface elevation inside the piezometer minus the water surface elevation of the river (m), and ΔL was the distance below the river bed to the top of the piezometer perforations (m). The VHG is a unit-less index with positive values indicative of upwelling (i.e., groundwater discharge zones) and negative values indicative of down-welling (i.e., groundwater recharge zones) (Freeze and Cherry 1979; Dahm and Valett 1996).

To demonstrate that we have been able to differentiate between groundwater and surface water using the internal drive-rod method, we provide measurements of water

surface elevation, VHG between groundwater and surface water, and electrical conductivity values that were collected from three piezometers (L2, L5, and L8) and the river in 1995 in the Hanford Reach. At the study site where the drive-point method has been used, the Columbia River lies on top of a relatively thick sequence of fluvial, lacustrine, and glaciofluvial sediments comprised of sand, gravel, and cobbles deposited during the cataclysmic Lake Missoula Floods (Schuster and Hays 1984; Dresel et al. 1995). The depth of this material usually exceeded 5 m where we installed piezometers; however, we occasionally encountered isolated patches of lower permeability material that were less than 5 m deep.

RESULTS AND DISCUSSION

The average installation depth for all piezometers installed in the Hanford Reach during 1995 ($n = 14$) was 175.0 cm (range 130.8 to 215.4 cm). After subtracting the length of the drive-point, open pipe, and perforations, the average depth from the river bed to the top of the piezometer perforations was 105.0 cm (range 60.8 to 145.4 cm). We were successful in 79% of the installation attempts in placing the perforated section of the piezometer at least 1 m below the river substrate. At several locations, it was not possible to install the perforated section of the piezometer to this depth even with repeated attempts; continued pounding on the piezometer eventually broke the weld on the drive-point. We suspect that patches of low permeability material were the reason for the 21% failure rate and not individual boulders, because the driven piezometer usually worked around boulders.

The air flow requirement of the impact hammer was $2.3 \text{ m}^3/\text{min}$. Piezometers could usually be driven to the desired depth within 10 to 15 minutes, depending on bed material, using the truck-mounted air compressor because it had a storage capacity of 120 L. However, the storage volume of the portable air compressor was smaller, and even though it was able to operate the hammer, the hammer depleted the stored volume before the compressor was able to replace it. When the portable air compressor was

used, the operator waited until the storage tank filled, drove for 30 seconds, and then waited for the tank to re-fill. Consequently, the impact time for installation of piezometers using the portable air compressor took approximately twice as long as with the truck-mounted air compressor. The use of the portable air compressor increased installation time, but usually did not prohibit driving piezometers to the desired depth and allowed access to remote sites.

We have used the internal drive-rod method in studies designed to investigate the occurrence of invertebrates that are found in the hyporheic zone. This required that un-screened piezometers be used. However, if the composition of fine sediment material in the hyporheic zone is significant, un-screened perforations can present a problem because fine sediment is able to enter the piezometer and accumulate to the point where the piezometer becomes clogged and un-responsive. We have noted this in approximately 25% of our installations in the Hanford Reach. This problem has been addressed by first removing the fine sediment, and then screening the perforated section *after* the piezometers are in place using stainless steel irrigation line-strainer screens (LST); a 2.5 cm dia. LST screen fits perfectly inside our piezometers. Following LST screen installation, the piezometers regained “connection” to water surface changes in the hyporheic zone; this has not changed after six months. Since 1995 we have successfully used the internal drive-rod method to install these piezometers with the LST screens welded in place prior to installation. This has prevented the recruitment of fine material into the piezometers and made for easier removal of the drive-rod. It has also allowed us to eliminate the sediment trap at the bottom of each piezometer, thereby increasing our effective penetration depth.

On the Hanford Site, shoreline seeps, surface water, and groundwater can be distinguished based on their relative electrical conductivity; Columbia River water is normally around 125 to 150 $\mu\text{S}/\text{cm}$, shoreline seeps range from 200 to 300 $\mu\text{S}/\text{cm}$, and undiluted groundwater is normally around 300 to 500 $\mu\text{S}/\text{cm}$ (Peterson and Johnson 1992; Dresel et al. 1995). Electrical conductivity measured within the river at all locations during 1995 averaged 132.9 $\mu\text{S}/\text{cm}$ (S.D. = $\pm 4.4 \mu\text{S}/\text{cm}$). Electrical

conductivity values measured within piezometers L2 and L8 during the same time period were similar to the river, and averaged $131.9 \mu\text{S}/\text{cm}$ (S.D. = $\pm 3.5 \mu\text{S}/\text{cm}$) and $144.1 \mu\text{S}/\text{cm}$ (S.D. = $\pm 20.4 \mu\text{S}/\text{cm}$), respectively (Figure 4.2a). The relative similarity between electrical conductivity values suggests that the hyporheic zone at these locations was comprised predominantly of river water, and it appeared to be upwelling into the river (Figure 4.2b). Electrical conductivity within piezometer L5, however, were higher and averaged $281.4 \mu\text{S}/\text{cm}$ (S.D. = $\pm 16.4 \mu\text{S}/\text{cm}$) over the same time period (Figure 4.2a). The elevated conductivity values observed at piezometer L5 indicated that a higher proportion of groundwater was present in the hyporheic zone at this location than was observed at other sites and it is also upwelling into the river (Figure 4.2b). Based on measurable differences in electrical conductivity within the piezometers and the presence of a measurable vertical potential between the hyporheic zone and the river, we were able to determine the proportion of groundwater and surface water in the hyporheic zone and to detect vertical potentials within highly permeable substrate.

The internal drive-rod method we describe here is a practical, cost-effective (each piezometer costs ~\$100-150 U.S.) way to access the hyporheic zones of large, alluvial rivers that contain coarse substrate. The internal drive-rod piezometers have successfully been used to differentiate between groundwater and surface water in large cobble-bed rivers. This innovative method provides information on the hydrodynamics of pore-waters in highly permeable, cobble deposits of high energy river and lake bottoms. Piezometers installed using the internal drive-rod method facilitate the assessment of the temporal and spatial dynamics of recharge and discharge at the groundwater/surface water interface and analyses of the ecological connectivity between the hyporheic zone and surface waters of rivers and streams.

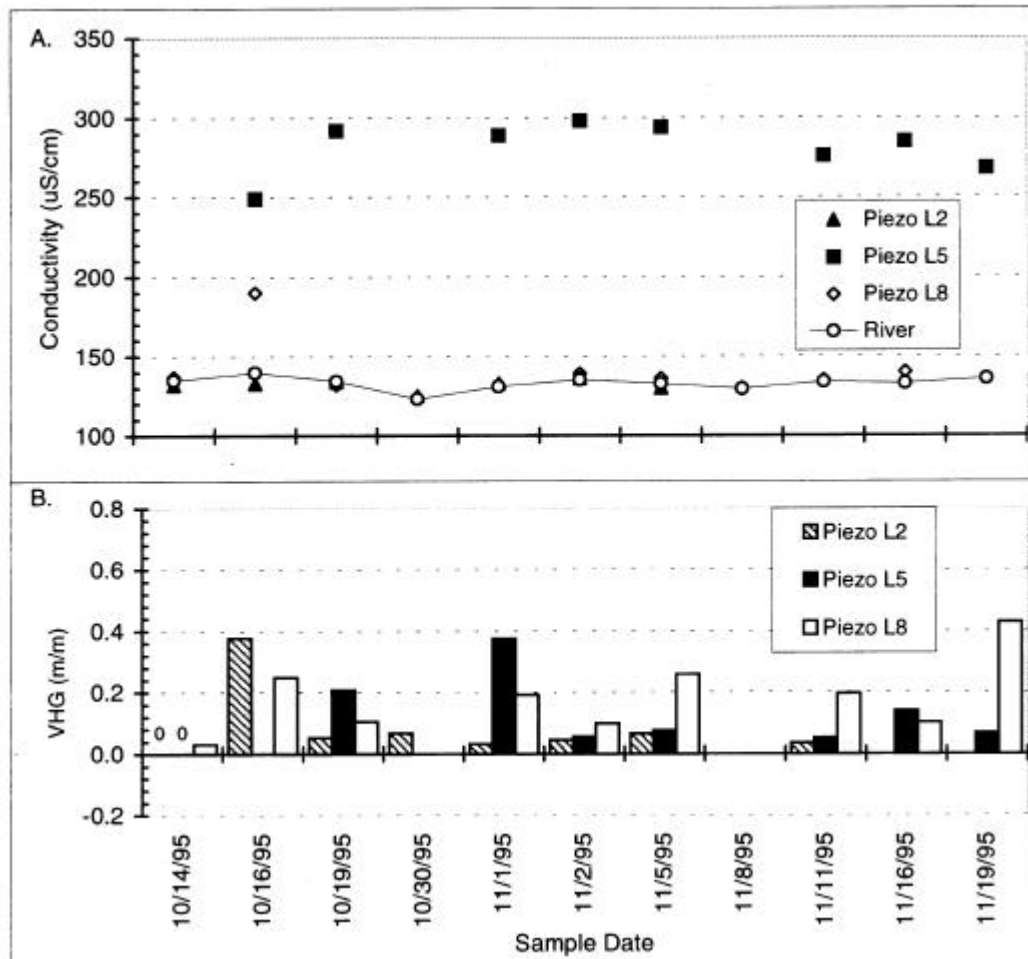


Figure 4.2. (a) Measurements of electrical conductivity, and (b) vertical hydraulic gradient (VHG) from the river and three piezometers (L2, L5, and L8) during October and November, 1995, in the Hanford Reach of the Columbia River. VHGs of 0.0 (indicated by zeros) were recorded in piezometers L2 and L5 on 14-November; the absence of a vertical bar on subsequent dates indicates no measurements of elevation were made.

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